
Kalman Filter Theory and Applications

Heuristic Overview

Michael L. Carroll

October 29, 2020

©2020 by Michael L. Carroll

Part I

The Basic Kalman Equations

Topics

Part I

The Basic Kalman Equations

Topics

- Understanding the Equations: Heuristic Introduction

Part I

The Basic Kalman Equations

Topics

- Understanding the Equations: Heuristic Introduction
- Equation Drilldown: Taking the Equations Apart

Part I

The Basic Kalman Equations

Topics

- Understanding the Equations: Heuristic Introduction
- Equation Drilldown: Taking the Equations Apart
- State Space Concepts

Part I

The Basic Kalman Equations

Topics

- Understanding the Equations: Heuristic Introduction
 - Equation Drilldown: Taking the Equations Apart
 - State Space Concepts
-

The Basic Kalman Equations

Understanding the Equations: Heuristic Introduction

Subtopics

The Basic Kalman Equations

Understanding the Equations: Heuristic Introduction

Subtopics

- Recursive Predictor-Corrector Algorithms

The Basic Kalman Equations

Understanding the Equations: Heuristic Introduction

Subtopics

- Recursive Predictor-Corrector Algorithms
- Running Averages

The Basic Kalman Equations

Understanding the Equations: Heuristic Introduction

Subtopics

- Recursive Predictor-Corrector Algorithms
- Running Averages
- Prediction (Extrapolation)

The Basic Kalman Equations

Understanding the Equations: Heuristic Introduction

Subtopics

- Recursive Predictor-Corrector Algorithms
- Running Averages
- Prediction (Extrapolation)
- **Correction (Measurement Update)**

The Basic Kalman Equations

Understanding the Equations: Heuristic Introduction

Subtopics

- Recursive Predictor-Corrector Algorithms
- Running Averages
- Prediction (Extrapolation)
- **Correction (Measurement Update)**
- Gain Computation

The Basic Kalman Equations

Understanding the Equations: Heuristic Introduction

Subtopics

- Recursive Predictor-Corrector Algorithms
 - Running Averages
 - Prediction (Extrapolation)
 - **Correction (Measurement Update)**
 - Gain Computation
-

Correction (Measurement Update)

The Measurement Model

Correction (Measurement Update)

The Measurement Model

- In the running average example, the update implicitly assumed that measurements were corrupted by white noise

Correction (Measurement Update)

The Measurement Model

- In the running average example, the update implicitly assumed that measurements were corrupted by white noise
- Measurement model for this would be:
$$z(k) = x(k) + v(k),$$
where $x(k)$ is the true state and $v(k)$ is measurement noise sequence

Correction (Measurement Update)

The Measurement Model

- In the running average example, the update implicitly assumed that measurements were corrupted by white noise
- Measurement model for this would be:
$$z(k) = x(k) + v(k),$$
where $x(k)$ is the true state and $v(k)$ is measurement noise sequence
- Simulated measurements are based on this: We provide a truth model and then add normally distributed measurement noise samples at time step k

Correction (Measurement Update)

The Measurement Model

- In the running average example, the update implicitly assumed that measurements were corrupted by white noise
- Measurement model for this would be:
$$z(k) = x(k) + v(k),$$
where $x(k)$ is the true state and $v(k)$ is measurement noise sequence
- Simulated measurements are based on this: We provide a truth model and then add normally distributed measurement noise samples at time step k
- Measurement processing is sometimes called **Observation** processing

Correction (Measurement Update)

The Measurement Model

- In the running average example, the update implicitly assumed that measurements were corrupted by white noise
 - Measurement model for this would be:
$$z(k) = x(k) + v(k),$$
where $x(k)$ is the true state and $v(k)$ is measurement noise sequence
 - Simulated measurements are based on this: We provide a truth model and then add normally distributed measurement noise samples at time step k
 - Measurement processing is sometimes called **Observation** processing
-

Correction (Measurement Update)

Correction (Measurement Update)

- Because we assumed that measurement noise was white Gaussian and zero mean, our best guess was simply the average value of all the measurements

Correction (Measurement Update)

- Because we assumed that measurement noise was white Gaussian and zero mean, our best guess was simply the average value of all the measurements
- Recall the resistor example: Voltmeter not perfect and each measurement differs slightly from previous one due to measurement noise, i.e., randomness in the voltmeter

Correction (Measurement Update)

- Because we assumed that measurement noise was white Gaussian and zero mean, our best guess was simply the average value of all the measurements
- Recall the resistor example: Voltmeter not perfect and each measurement differs slightly from previous one due to measurement noise, i.e., randomness in the voltmeter
- This randomness is completely independent of any noise that might be disturbing the dynamic process itself

Correction (Measurement Update)

- Because we assumed that measurement noise was white Gaussian and zero mean, our best guess was simply the average value of all the measurements
 - Recall the resistor example: Voltmeter not perfect and each measurement differs slightly from previous one due to measurement noise, i.e., randomness in the voltmeter
 - This randomness is completely independent of any noise that might be disturbing the dynamic process itself
-

Correction (Measurement Update)

Correction (Measurement Update)

- General Kalman filtering complicates the measurement model by adding two new elements:

Correction (Measurement Update)

- General Kalman filtering complicates the measurement model by adding two new elements:
 - The measurement may have a more complicated relationship to the underlying system state:

$$z(k) = h[k, x(k)] + v(k),$$

where h could be a non-linear function with possible explicit time dependence

Correction (Measurement Update)

- General Kalman filtering complicates the measurement model by adding two new elements:
 - The measurement may have a more complicated relationship to the underlying system state:

$$z(k) = h[k, x(k)] + v(k),$$

where h could be a non-linear function with possible explicit time dependence

- Just as the state x is allowed to be a vector variable, so the measurement z could also be a vector variable

Correction (Measurement Update)

- General Kalman filtering complicates the measurement model by adding two new elements:
 - The measurement may have a more complicated relationship to the underlying system state:

$$z(k) = h[k, x(k)] + v(k),$$

where h could be a non-linear function with possible explicit time dependence

- Just as the state x is allowed to be a vector variable, so the measurement z could also be a vector variable
- This means that we can measure several different quantities simultaneously, or use redundant measurements of the same quantities from different sensors

Correction (Measurement Update)

- General Kalman filtering complicates the measurement model by adding two new elements:
 - The measurement may have a more complicated relationship to the underlying system state:

$$z(k) = h[k, x(k)] + v(k),$$

where h could be a non-linear function with possible explicit time dependence

- Just as the state x is allowed to be a vector variable, so the measurement z could also be a vector variable
- This means that we can measure several different quantities simultaneously, or use redundant measurements of the same quantities from different sensors
- Note that the measurement model is a direct algebraic equation, not a differential equation nor a difference equation

Correction (Measurement Update)

Recursive Running Average Revisited

Correction (Measurement Update)

Recursive Running Average Revisited

- Recall the recursive formulation of the running average

Correction (Measurement Update)

Recursive Running Average Revisited

- Recall the recursive formulation of the running average
- We used the latest measurement to **update** (or **correct**) the last estimate:

Correction (Measurement Update)

Recursive Running Average Revisited

- Recall the recursive formulation of the running average
- We used the latest measurement to **update** (or **correct**) the last estimate:

$$\hat{x}^+(k) = \hat{x}^-(k) + K [z(k) - \hat{x}^-(k)] \quad (1)$$

where the gain is $K = \frac{1}{n}$

Correction (Measurement Update)

Recursive Running Average Revisited

- Recall the recursive formulation of the running average
- We used the latest measurement to **update** (or **correct**) the last estimate:

$$\hat{x}^+(k) = \hat{x}^-(k) + K [z(k) - \hat{x}^-(k)] \quad (1)$$

where the gain is $K = \frac{1}{n}$

- Note the use of $\hat{x}^-(k)$ in the measurement residual. Ordinarily, we would use $h(\hat{x}^-(k))$ instead because the measurement is a function of the state (e.g., it might be in different units of measurement than the state variable)

Correction (Measurement Update)

Recursive Running Average Revisited

- Recall the recursive formulation of the running average
- We used the latest measurement to **update** (or **correct**) the last estimate:

$$\hat{x}^+(k) = \hat{x}^-(k) + K [z(k) - \hat{x}^-(k)] \quad (1)$$

where the gain is $K = \frac{1}{n}$

- Note the use of $\hat{x}^-(k)$ in the measurement residual. Ordinarily, we would use $h(\hat{x}^-(k))$ instead because the measurement is a function of the state (e.g., it might be in different units of measurement than the state variable)
-

Correction (Measurement Update)

Simultaneous Measurements

Correction (Measurement Update)

Simultaneous Measurements

- If we had two voltmeters and make simultaneous measurements of the resistance, our measurement model would look like this

Correction (Measurement Update)

Simultaneous Measurements

- If we had two voltmeters and make simultaneous measurements of the resistance, our measurement model would look like this

$$\begin{bmatrix} z_1(k) \\ z_2(k) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} + \begin{bmatrix} v_1(k) \\ v_2(k) \end{bmatrix}$$

Correction (Measurement Update)

Simultaneous Measurements

- If we had two voltmeters and make simultaneous measurements of the resistance, our measurement model would look like this

$$\begin{bmatrix} z_1(k) \\ z_2(k) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} + \begin{bmatrix} v_1(k) \\ v_2(k) \end{bmatrix}$$

- Here the h function is a simple 2x2 identity matrix

Correction (Measurement Update)

Simultaneous Measurements

- If we had two voltmeters and make simultaneous measurements of the resistance, our measurement model would look like this

$$\begin{bmatrix} z_1(k) \\ z_2(k) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} + \begin{bmatrix} v_1(k) \\ v_2(k) \end{bmatrix}$$

- Here the h function is a simple 2x2 identity matrix
- The noise for each voltmeter would likely be different, unless these units were considered to be identical in precision

Correction (Measurement Update)

Simultaneous Measurements

- If we had two voltmeters and make simultaneous measurements of the resistance, our measurement model would look like this

$$\begin{bmatrix} z_1(k) \\ z_2(k) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} + \begin{bmatrix} v_1(k) \\ v_2(k) \end{bmatrix}$$

- Here the h function is a simple 2x2 identity matrix
- The noise for each voltmeter would likely be different, unless these units were considered to be identical in precision
- The solution of the Kalman gain assumes that the h is a matrix; the letter H is conventionally reserved for the measurement matrix

Correction (Measurement Update)

Simultaneous Measurements

- If we had two voltmeters and make simultaneous measurements of the resistance, our measurement model would look like this

$$\begin{bmatrix} z_1(k) \\ z_2(k) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} + \begin{bmatrix} v_1(k) \\ v_2(k) \end{bmatrix}$$

- Here the h function is a simple 2x2 identity matrix
- The noise for each voltmeter would likely be different, unless these units were considered to be identical in precision
- The solution of the Kalman gain assumes that the h is a matrix; the letter H is conventionally reserved for the measurement matrix

Correction (Measurement Update) Summary

Vector Check

Correction (Measurement Update) Summary

Vector Check

- Where are we?

Correction (Measurement Update) Summary

Vector Check

- Where are we?
 - Discussed how estimates are updated using measurements and a **measurement model**

Correction (Measurement Update) Summary

Vector Check

- Where are we?
 - Discussed how estimates are updated using measurements and a **measurement model**
 - Revisited the running average and examined its measurement model

Correction (Measurement Update) Summary

Vector Check

- Where are we?
 - Discussed how estimates are updated using measurements and a **measurement model**
 - Revisited the running average and examined its measurement model
- What's next?

Correction (Measurement Update) Summary

Vector Check

- Where are we?
 - Discussed how estimates are updated using measurements and a **measurement model**
 - Revisited the running average and examined its measurement model
- What's next?
 - In the next video we will talk about the computation of the Kalman gain

Correction (Measurement Update) Summary

Vector Check

- Where are we?
 - Discussed how estimates are updated using measurements and a **measurement model**
 - Revisited the running average and examined its measurement model
- What's next?
 - In the next video we will talk about the computation of the Kalman gain
 - Discuss the notion of the *measurement residual*

Correction (Measurement Update) Summary

Vector Check

- Where are we?
 - Discussed how estimates are updated using measurements and a **measurement model**
 - Revisited the running average and examined its measurement model
 - What's next?
 - In the next video we will talk about the computation of the Kalman gain
 - Discuss the notion of the *measurement residual*
-