Kalman Filter Theory and Applications Equation Drilldown

Michael L. Carroll

November 1, 2020

©2020 by Michael L. Carroll

• Mathematical Formulation of the Problem

- Mathematical Formulation of the Problem
- Drilldown on State Dynamics and Covariance Extrapolation Equations

- Mathematical Formulation of the Problem
- Drilldown on State Dynamics and Covariance Extrapolation Equations
- The Five Kalman Filter Equations

- Mathematical Formulation of the Problem
- Drilldown on State Dynamics and Covariance Extrapolation Equations
- The Five Kalman Filter Equations
- Examples

- Mathematical Formulation of the Problem
- Drilldown on State Dynamics and Covariance Extrapolation Equations
- The Five Kalman Filter Equations
- Examples
- Exercises

- Mathematical Formulation of the Problem
- Drilldown on State Dynamics and Covariance Extrapolation Equations
- The Five Kalman Filter Equations
- Examples
- Exercises

The Kalman Filter Solution: The Kalman Gain

The Kalman Filter Solution: The Kalman Gain

• The heart of the solution is the **Kalman Gain**: K(k)

The Kalman Filter Solution: The Kalman Gain

• The heart of the solution is the **Kalman Gain**: K(k)

$$K(k) = P^{-}(k) H(k)^{\top} \left[H(k) P^{-}(k) H(k)^{\top} + R(k) \right]^{-1}$$
 (1)

where R(k) is the measurement noise covariance matrix (to be defined later) governing the white measurement noise v(k) in the measurement model:

$$z(k) = H(k)x(k) + v(k)$$

The Kalman Filter Solution: The Kalman Gain

• The heart of the solution is the **Kalman Gain**: K(k)

$$K(k) = P^{-}(k) H(k)^{\top} \left[H(k) P^{-}(k) H(k)^{\top} + R(k) \right]^{-1}$$
 (1)

where R(k) is the measurement noise covariance matrix (to be defined later) governing the white measurement noise v(k) in the measurement model:

$$z(k) = H(k)x(k) + v(k)$$

The Kalman Filter Solution: State Update Equation

The Kalman Filter Solution: State Update Equation

 Using the gain, the state update equation (which we've already seen) is

$$\hat{x}^{+}(k) = \hat{x}^{-}(k) + K(k) \left[z(k) - H(k)\hat{x}^{-}(k) \right]$$
 (2)

where z(k) is the measurement and H(k) is the measurement matrix at time k.

The Kalman Filter Solution: State Update Equation

 Using the gain, the state update equation (which we've already seen) is

$$\hat{x}^{+}(k) = \hat{x}^{-}(k) + K(k) \left[z(k) - H(k)\hat{x}^{-}(k) \right]$$
 (2)

where z(k) is the measurement and H(k) is the measurement matrix at time k.

15

• Likewise, the error covariance P(k) is corrected using the gain:

$$P^{+}(k) = [I - K(k)H(k)]P^{-}(k)$$
(3)

• Likewise, the error covariance P(k) is corrected using the gain:

$$P^{+}(k) = [I - K(k)H(k)]P^{-}(k)$$
(3)

• This is not a good form to use in numerical work!

• Likewise, the error covariance P(k) is corrected using the gain:

$$P^{+}(k) = [I - K(k)H(k)]P^{-}(k)$$
(3)

- This is not a good form to use in numerical work!
- Better to use the Joseph form:

• Likewise, the error covariance P(k) is corrected using the gain:

$$P^{+}(k) = [I - K(k)H(k)]P^{-}(k)$$
(3)

- This is not a good form to use in numerical work!
- Better to use the Joseph form:

$$P^{+}(k) = [I - K(k)H(k)]P^{-}(k)[I - K(k)H(k)]^{\top} + K(k)R(k)K(k)^{\top}$$

• Likewise, the error covariance P(k) is corrected using the gain:

$$P^{+}(k) = [I - K(k)H(k)]P^{-}(k)$$
(3)

- This is not a good form to use in numerical work!
- Better to use the Joseph form:

$$P^{+}(k) = [I - K(k)H(k)]P^{-}(k)[I - K(k)H(k)]^{\top} + K(k)R(k)K(k)^{\top}$$

Better preserves symmetry of P

• Likewise, the error covariance P(k) is corrected using the gain:

$$P^{+}(k) = [I - K(k)H(k)]P^{-}(k)$$
(3)

- This is not a good form to use in numerical work!
- Better to use the Joseph form:

$$P^{+}(k) = [I - K(k)H(k)]P^{-}(k)[I - K(k)H(k)]^{\top} + K(k)R(k)K(k)^{\top}$$

Better preserves symmetry of P

State Extrapolation:
$$\hat{x}^-(k) = \Phi(k)\hat{x}^+(k-1)$$
 (4)

State Extrapolation:
$$\hat{x}^-(k) = \Phi(k)\hat{x}^+(k-1)$$
 (4)

Covariance Extrapolation:
$$P^{-}(k) = \Phi(k)P^{+}(k-1)\Phi(k)^{\top} + Q(k)$$
 (5)

State Extrapolation:
$$\hat{x}^-(k) = \Phi(k)\hat{x}^+(k-1)$$
 (4)

Covariance Extrapolation:
$$P^{-}(k) = \Phi(k)P^{+}(k-1)\Phi(k)^{\top} + Q(k)$$
 (5)

Kalman Gain:
$$K(k) = P^{-}(k) H(k)^{\top} \left[H(k) P^{-}(k) H(k)^{\top} + R(k) \right]^{-1}$$
 (6)

State Extrapolation:
$$\hat{x}^-(k) = \Phi(k)\hat{x}^+(k-1)$$
 (4)

Covariance Extrapolation:
$$P^{-}(k) = \Phi(k)P^{+}(k-1)\Phi(k)^{\top} + Q(k)$$
 (5)

Kalman Gain:
$$K(k) = P^{-}(k) H(k)^{\top} \left[H(k) P^{-}(k) H(k)^{\top} + R(k) \right]^{-1}$$
 (6)

State Update:
$$\hat{x}^{+}(k) = \hat{x}^{-}(k) + K(k) [z(k) - H(k)\hat{x}^{-}(k)]$$
 (7)

State Extrapolation:
$$\hat{x}^-(k) = \Phi(k)\hat{x}^+(k-1)$$
 (4)

Covariance Extrapolation:
$$P^{-}(k) = \Phi(k)P^{+}(k-1)\Phi(k)^{\top} + Q(k)$$
 (5)

Kalman Gain:
$$K(k) = P^{-}(k) H(k)^{\top} \left[H(k) P^{-}(k) H(k)^{\top} + R(k) \right]^{-1}$$
 (6)

State Update:
$$\hat{x}^{+}(k) = \hat{x}^{-}(k) + K(k) [z(k) - H(k)\hat{x}^{-}(k)]$$
 (7)

Covariance Update:
$$P^{+}(k) = [I - K(k)H(k)]P^{-}(k)$$
 (8) or $P^{+}(k) = [I - K(k)H(k)]P^{-}(k)[I - K(k)H(k)]^{\top} + K(k)R(k)K(k)^{\top}$

State Extrapolation:
$$\hat{x}^-(k) = \Phi(k)\hat{x}^+(k-1)$$
 (4)

Covariance Extrapolation:
$$P^{-}(k) = \Phi(k)P^{+}(k-1)\Phi(k)^{\top} + Q(k)$$
 (5)

Kalman Gain:
$$K(k) = P^{-}(k) H(k)^{\top} \left[H(k) P^{-}(k) H(k)^{\top} + R(k) \right]^{-1}$$
 (6)

State Update:
$$\hat{x}^{+}(k) = \hat{x}^{-}(k) + K(k) [z(k) - H(k)\hat{x}^{-}(k)]$$
 (7)

Covariance Update:
$$P^{+}(k) = [I - K(k)H(k)]P^{-}(k)$$
 (8) or $P^{+}(k) = [I - K(k)H(k)]P^{-}(k)[I - K(k)H(k)]^{\top} + K(k)R(k)K(k)^{\top}$

28

• $P^+(k) = \mathbb{E}\left[\tilde{x}^+(k)\left[\tilde{x}^+(k)\right]^\top\right]$ is the estimation error covariance matrix Often just referred to as the 'covariance matrix'

- $P^+(k) = \mathsf{E}\left[\tilde{x}^+(k)\left[\tilde{x}^+(k)\right]^\top\right]$ is the estimation error covariance matrix Often just referred to as the 'covariance matrix'
- $\tilde{x}^+(k) = \hat{x}^+(k) x(k)$ is the estimation error

- $P^+(k) = \mathbb{E}\left[\tilde{x}^+(k)\left[\tilde{x}^+(k)\right]^\top\right]$ is the estimation error covariance matrix

 Often just referred to as the 'covariance matrix'
- $\tilde{x}^+(k) = \hat{x}^+(k) x(k)$ is the estimation error
- $Q(k) := E[w(k)w(k)^{\top}]$ is the process noise covariance matrix

- $P^+(k) = \mathbb{E}\left[\tilde{x}^+(k)\left[\tilde{x}^+(k)\right]^\top\right]$ is the estimation error covariance matrix Often just referred to as the 'covariance matrix'
- $\tilde{x}^+(k) = \hat{x}^+(k) x(k)$ is the estimation error
- $Q(k) := E[w(k)w(k)^{\top}]$ is the process noise covariance matrix
- $R(k) := E[v(k)v(k)^{T}]$ is the measurement noise covariance matrix

- $P^+(k) = \mathbb{E}\left[\tilde{x}^+(k)\left[\tilde{x}^+(k)\right]^\top\right]$ is the estimation error covariance matrix Often just referred to as the 'covariance matrix'
- $\tilde{x}^+(k) = \hat{x}^+(k) x(k)$ is the estimation error
- $Q(k) := E[w(k)w(k)^{\top}]$ is the process noise covariance matrix
- $R(k) := E\left[v(k)v(k)^{\top}\right]$ is the measurement noise covariance matrix

• Where are we?

- Where are we?
 - Introduced R and drilled down on the Kalman gain equation as a function of P, Q, R

- Where are we?
 - Introduced R and drilled down on the Kalman gain equation as a function of P, Q, R
 - Showed how Kalman gain K is used to update covariance P

- Where are we?
 - Introduced R and drilled down on the Kalman gain equation as a function of P, Q, R
 - Showed how Kalman gain K is used to update covariance P
 - Presented all five Kalman filter equations

- Where are we?
 - Introduced R and drilled down on the Kalman gain equation as a function of P, Q, R
 - Showed how Kalman gain K is used to update covariance P
 - Presented all five Kalman filter equations
- What's next?

- Where are we?
 - Introduced R and drilled down on the Kalman gain equation as a function of P, Q, R
 - Showed how Kalman gain K is used to update covariance P
 - Presented all five Kalman filter equations
- What's next?
 - Examples: From simple scalar to more complex vector applications

- Where are we?
 - Introduced R and drilled down on the Kalman gain equation as a function of P, Q, R
 - Showed how Kalman gain K is used to update covariance P
 - Presented all five Kalman filter equations
- What's next?
 - Examples: From simple scalar to more complex vector applications