CDISE
Mobile Robotics Lab
Perception in Robotics Course

L04: Bayes filter and Kalman filter

Gonzalo Ferrer

8 February 2021

1 Bayes filter general form

z : Observations → Sensors obtain information
u : Actions → Change the state of the world
x : State → Robot representation and its environment
Sensor model: $p(z_t|x_t)$ — measurement probability
Action model: $p(x_t|x_{t-1}, u_t)$ — state transition probability
Belief: $bel(x_t)$ — posterior of the state

$$\text{Bel}(x_t) = p(x_t|u_1, z_1, \dots, u_t, z_t) = p(x_t|u_{1:t}, z_{1:t}) \tag{1}$$

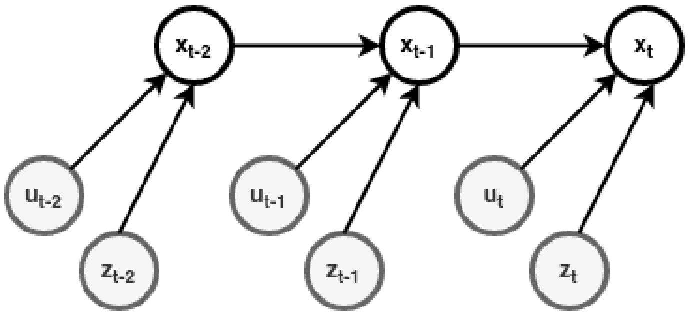

Figure 1: Graphical model

If x is complete (Markovian assumption):

$$p(x_t|x_{0:t-1}, z_{1:t-1}, u_{1:t}) = p(x_t|x_{t-1}, u_t)$$
$$p(z_t|x_{0:t}, z_{1:t-1}, u_{1:t}) = p(z_t|x_t)$$

$$\begin{aligned}
\text{Bel}(x_t) &= p(x_t|u_{1:t}, z_{1:t}) \\
&= \eta p(z_t|x_t, u_{1:t}, z_{1:t-1}) p(x_t|u_{1:t}, z_{t-1}) && \text{(Bayes)} \\
&= \eta p(z_t|x_t) p(x_t|u_{1:t}, z_{1:t-1}) && \text{(Markov)} \\
&= \eta p(z_t|x_t) \int_{x_{t-1}} p(x_t|u_{1:t}, z_{1:t-1} x_{t-1}) p(x_{t-1}|u_{1:t}, z_{1:t-1}) dx_{t-1} && \text{(Total prob)} \\
&= \eta p(z_t|x_t) \int_{x_{t-1}} p(x_t|u_t, x_{t-1}) p(x_{t-1}|u_{1:t-1}, z_{1:t-1}) dx_{t-1} \\
&= \eta p(z_t|x_t) \int_{x_{t-1}} p(x_t|u_t, x_{t-1}) p(x_{t-1}) dx_{t-1} && \text{(Recursive form)}
\end{aligned}$$

2 Bayes filter algorithm

$$\boxed{\begin{aligned} &\overline{bel}(x_t) = \int p(x_t|u_t, x_{t-1}) bel(x_{t-1}) dx_{t-1} \\ &\qquad \uparrow\downarrow \\ &bel(x_t) = \eta p(z_t|x_t)\overline{bel}(x_t) \end{aligned}}$$

3 Kalman filter: Linear Dynamic system

We will derive it directly from the Bayes filter assuming a prior to be Gaussian:

$$x_{t-1} \sim \mathcal{N}(\mu_{t-1}, \Sigma_{t-1}) \tag{2}$$

3.1 (State) transition function

$$x_t = A_t x_{t-1} + B_t u_t + \varepsilon_t \quad , \quad \varepsilon_t \sim \mathcal{N}(0, R) \tag{3}$$

Linear function plus added Gaussian noise $\Rightarrow$ x_t is Gaussian

$$x_t = \begin{bmatrix} x_{1,t} \\ x_{1,t} \\ \vdots \\ x_{n,t} \end{bmatrix}, \quad u_t = \begin{bmatrix} u_{1,t} \\ \vdots \\ u_{m,t} \end{bmatrix}, \quad A_t = \mathbb{R}^{n \times n}, \quad B_t = \mathbb{R}^{n \times m} \tag{4}$$

3.2 Observation function

$$z_t = C_t x_t + \delta_t, \quad \delta_t \sim \mathcal{N}(O, Q) \tag{5}$$

Linear function, δ_t is Gaussian, x_t is Gaussian $\Rightarrow$ z_t is Gaussian

$$z_t = \begin{bmatrix} z_{1,t} \\ z_{1,t} \\ \vdots \\ z_{k,t} \end{bmatrix}, \quad C_t = \mathbb{R}^{k \times n}, \quad Q \in \mathbb{R}^{k \times k} \tag{6}$$

3.3 Kalman filter: Linear case

— Transition function is linear
— Observation function is linear
— Priors states and noise Gaussians
Then, KF (Kalman Filter) is BLUE (Best Linear Unbiased Estimator)

$$\begin{aligned} \text{I:} \quad & \overline{\mu_t} = A_t \mu_{t-1} + B_t u_t \\ \text{II:} \quad & \overline{\Sigma_t} = A_t \Sigma_{t-1} A_t^T + R \\ \text{III:} \quad & K_t = \overline{\Sigma}_t C_t^T (C_t \overline{\Sigma}_t C_t^T + Q)^{-1} \\ \text{IV:} \quad & \mu_t = \overline{\mu}_t + K_t (z_t - C_t \overline{\mu}_t) \\ \text{V:} \quad & \Sigma_t = (I - K_t C_t) \overline{\Sigma}_t \end{aligned}$$

Output $bel(x_t) = \mathcal{N}(\mu_{t_i} \Sigma_t)$ becomes the input prior on the next iteration.

4 Derivation of the prediction step $\overline{bel}(x_t)$

$$\overline{\mu}_t = \mathbb{E}\{x_t \,|\, u_{1:t}, z_{1:t}\} = \mathbb{E}\{A_t x_{t-1} + B_t u_t + \varepsilon_t |\, \theta\} = A_t \mu_{t-1} + B_t \mu_t$$

In this derivation, we will use the auxiliary variable θ to express the past history of observations and odometry values. We will also include the observation z_t, although it does not affect the current transition, but it will be useful to derive the posterior distribution without any artificial assumption.

$$\begin{aligned}
\overline{\Sigma}_t &= \mathbb{E}\{(x_t - \overline{\mu}_t)(x_t - \overline{\mu}_t) |\, \theta\} = \\
&= \mathbb{E}\{(A_t x_{t-1} + B_t \mu_t + \varepsilon_t - A_t \mu_{t-1} - B_t \mu_t)(A_t x_{t-1} + \varepsilon_t - A_t \mu_{t-1})^T \,|\, \theta\} \\
&= \mathbb{E}\{(A_t (x_{t-1} - \mu_{t-1}) + \varepsilon_t)(A_t (x_{t-1} - \mu_{t-1}) + \varepsilon_t)^T \,|\, \theta\} \\
&= \mathbb{E}\{A_t (x_{t-1} - \mu_{t-1})(x_{t-1} - \mu_{t-1})^T A_t^T + \varepsilon_t \varepsilon_t^T + \varepsilon_t (x_{t-1} - \mu_{t-1})^T A_t^T + \\
&+ A_t (x_{t-1} - \mu_{t-1}) \varepsilon_t^T \,|\, \theta\} \\
&\varepsilon, x - \text{uncorrelated} \quad \text{and } \mathbb{E}\{\varepsilon_t\} = 0 \\
&= A_t \cdot \Sigma_{t-1} \cdot A_t^T + R
\end{aligned}$$

Now we build the joint probability

$$p(x_t, x_{t-1} \,|\, \theta) = \mathcal{N}\left(\begin{bmatrix} \overline{\mu}_t \\ \mu_{t-1} \end{bmatrix}, \quad \begin{bmatrix} A_t \Sigma_{t-1} A_t^T + R & - \\ - & \Sigma_{t-1} \end{bmatrix} \right). \tag{7}$$

Then, we marginalize this expression in order to obtain a PDF dependent only on the variable x_t:

$$\overline{bel}(x_t) = p(x_t \,|\, \theta) = \int p(x_t, x_{t-1} \,|\, \theta) dx_{t-1}.$$

Note that the result of the I and II steps coincides with the expression of the DPF we have just marginalized, for $\overline{\mu}_t$ and the block matrix in the top-left corner of the covariance above.

5 Derivation of the correction step $bel(x_t)$

Build the joint Gaussian PDF (similarly as before)

$$p(z_t, x_t | u_{1:t}, z_{1:t-1}) = p(z_t | x_t, \theta)\, \overline{bel}(x_t) \tag{8}$$

then condition this PDF on z_t to obtain the posterior of x_t or belief $bel(x_t)$

$$\begin{aligned}
\mu_z &= \mathbb{E}\{z_t \,|\, \theta\} = \mathbb{E}\{C_t x_t + \delta_t \,|\, \theta\} = C_t \overline{\mu}_t \\
\Sigma_z &= \mathbb{E}\{(z_t - \mu_z)(z_t - \mu_z)^T \,|\, \theta\} \\
&= \mathbb{E}\{C_t x_t + \delta_t - C_t \overline{\mu}_t)(C_t x_t + \delta_t - C_t \overline{\mu}_t)^T \,|\, \theta\} \\
&= \mathbb{E}\{C_t (x_t - \overline{\mu}_t)(x_t - \overline{\mu}_t)^T C_t^T + \delta_t () x_t^T + \delta_t \delta_t^T \,|\, \theta\} \\
&(\delta_t, x_t \quad \text{are uncorrelated and } \mathbb{E}\{\delta_t\} = 0.) \\
&= C_t \overline{\Sigma}_t C_t^T + Q \\
\Sigma_{x,z} &= cov(x_t, z_t) = \mathbb{E}\{(x_t - \mu_t)(z_t - \mu_z)^T \,|\, \theta\} \\
&= \mathbb{E}\{(x_t - \overline{\mu}_t)(C_t x_t + \delta_t - C_t \overline{\mu}_t)^T \,|\, \theta\} = \\
&= \mathbb{E}\{(x_t - \overline{\mu}_t)(x_t - \overline{\mu}_t)^T C^T + x_t \delta_t - \mu_t \delta_t \,|\, \theta\} = \overline{\Sigma}_t C_t^T
\end{aligned}$$

$$p(x_t, z_t | \mu_{1:t}, z_{1:t-1}) = N\left(\begin{bmatrix} C_t\overline{\mu}_t \\ \overline{\mu}_t \end{bmatrix}, \quad \begin{bmatrix} C_t\overline{\Sigma}_t C_t^T + Q & C_t\overline{\Sigma}_t \\ \overline{\Sigma}_t C_t^T & \overline{\Sigma}_t \end{bmatrix}\right)$$

$$\begin{aligned}
p(x_t | z_t, \mu_{1:t}, z_{1:t-1}) = bel(x_t) &= \mathcal{N}(\overline{\mu}_t + \Sigma_{z,x}\Sigma_z^{-1}(z_t - \mu_z), \overline{\Sigma}_t - \Sigma_{x,z}\Sigma_z^{-1}\Sigma_{z,x}) \\
\mu_t &= \overline{\mu}_t + \underbrace{\overline{\Sigma}_t C_t^T (C_t\Sigma_t C_t^T + Q)^{-1}}_{K_t \quad \text{(III)}}(z_t - C_t\overline{\mu}_t) = \\
&= \overline{\mu}_t + k_t(z_t - C_t\overline{\mu}_t) \quad \text{(IV)} \\
\Sigma_t &= \overline{\Sigma}_t - \underbrace{\overline{\Sigma}_t C_t^T (C_t\overline{\Sigma}_t C_t^T + Q)^{-1}}_{K_t} C_t\overline{\Sigma}_t = (I - k_t C_t)\overline{\Sigma}_t \quad \text{(V)}
\end{aligned}$$

KF
— Highly efficient $O(k^3 + n^2)$
— Optimal for linear Gaussian systems
— Most real world system are non-linear.

6 Summary

In this lecture, we have described the following:

Bayes filter

$$\overline{bel}(x_t) = \int p(x_t | x_{t-1}, u_t bel(x_{t-1})$$

$$bel(x_t) = \eta p(z_t | x_t)\overline{bel}(x_t)$$

Kalman filter: Bayes filter for linear system and Gaussians

prediction (Steps I, II)	Marginalization G's
correction (Steps III, IV, V)	Conditioning G's

$$\begin{cases} x_t &= g(x_{t-1}, u_t, \varepsilon_t) = A_t x_{t-1} + B_t u_t + \varepsilon_t \\ z_t &= h(x_t, \delta_t) = C_t x_t + \delta_t \end{cases}$$