Reference : Probabilistic Robotics by S. Thrun et al

Roadmap.

- Localization / estimation problem
- Review of Bayes rule
- One step estimation
- Multi-step estimation Bayes filter algorithm
  Histogram filter

Basic problem of localization / State estimation

State is evolving based on input and noisy dynamics

$$x_{t+1} = f(x_t, u_t) + \omega_t$$

x_t : State $\longrightarrow$ we cannot observe / measure this directly

u_t : Control input $\rightarrow$ This is known

f, ω : model noise $\rightarrow$ we know model and distribution for ω_t

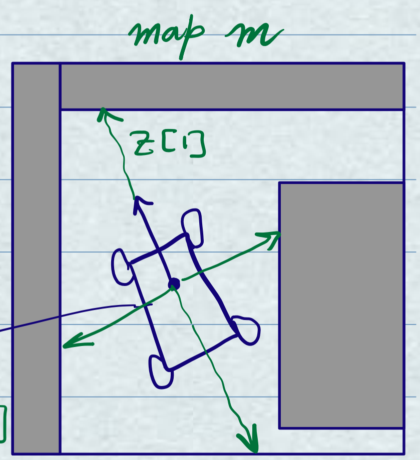
$$z_t = h(x_t)$$

z_t : measurement

g : measurement model

$\vec{x} = (x, y, \theta)$

$z_t = \langle z_t[1], \dots z_t[4] \rangle$



How to use measurements to improve estimation of x_t.

Review of Bayes Rule / Conditional probability

X : Random variable taking values
$x_1, x_2 \ldots x_k$

$P(X = x_i)$ written in short as $P(x_i)$

$P(X = x_i, Z = z_j)$ written as $P(x_i, y_j)$

$P(X = x \mid Z = z)$ Conditional probability of $X = x$ given

<u>Def.</u> $$P(x \mid z) = \frac{P(x, z)}{P(z)} \quad \text{— (1)}$$

Provided $P(z) > 0$

i.e. $$P(x, z) = P(x \mid z)\, P(z)$$

$$P(z \mid x) = \frac{P(x, z)}{P(x)}$$

$$P(x, z) = P(z \mid x)\, P(x) \quad \text{— (3)}$$

Replacing (3) in (1)

Bayes Rule

$$P(x \mid z) = \frac{P(z \mid x)\, P(x)}{P(z)}$$

Prior

Posterior

inverse Conditional Prob

$$\boxed{P(x \mid y, z) = \frac{P(y \mid x, z)\, P(x \mid z)}{P(y \mid z)}} \qquad 4$$

Derive this (exercise)

$$P(x \mid y, z) = \frac{P(x\, y\, z)}{P(y, z)} \qquad P(z) > 0$$

$= P(y \mid x, z)$.

$$= \frac{P(y \mid x\, z)\, P(x, z)}{P(y\, z)}$$

$$= \frac{P(y \mid x, z)\, P(x \mid z)\, \cancel{P(z)}}{P(y \mid z)\, \cancel{P(z)}}$$

Law of total probability

$$\sum_{x_i} P(X = x_i) = \sum_{x_i} P(x_i) = 1$$

$$P(Y = y_j) = \sum_{x_i} P(Y = y_j \wedge X = x_i) = \sum_{x_i} P(y \mid x_i)\, P(x_i)$$

$$P(Y = y_j) = \int_{x_i} P(y_j \mid x_i)\, P(x_i)\, dx_i$$

in the continuous setting

In our estimation problem (one shot)

X : position

: measurement

$P(X=x)$: Prior knowledge about position

$P(X=x \mid Z=z)$: Posterior

$P(Z=z \mid X=x)$: Generative model for measurements (analogous to g)

$P(z)$: does not depend on X

- normalization constant $\eta = 1/P($)

$$P(x \mid z) = \eta \, P(z \mid x) \, P(x)$$

Estimation over a sequence of steps

State evolves in discrete steps

$X_1 = x_1 \quad X_2 = x_2 \quad \cdots\cdots$ Sequence of RVs

$P(X_{t+1} = x_{t+1} \mid X_t = x_t) \qquad P(x_{t+1} \mid x_t)$

↑ State evolution model

In case there is no noise or input

$$P(X_{t+1} = f(x_t) \mid X_t = x_t) = \underline{1}$$

With inputs and measurements

$$\begin{aligned} P(X_t = x_t \mid\ & X_0 = x_0,\ X_1 = x_1 \ \cdots\ X_t = x_{t-1} \\ & U_1 = u_1 \ \ U_2 = u_2 \ \cdots\ U_{t-1} = u_{t-1} \\ & Z_1 = z_1 \ \cdots\ Z_{t-1} = z_{t-1}) \end{aligned}$$

We write in brief as

$$P(x_t \mid x_{0:t-1}, z_{1:t-1}, u_{1:t-1})$$

We assume Markovian State evolution model

$$P(x_t \mid x_{0:t-1}, z_{1:t-1}, u_{1:t-1}) = P(x_t \mid x_{t-1}, u_{t-1})$$

We also write this as

$$P(x' \mid x, u)$$

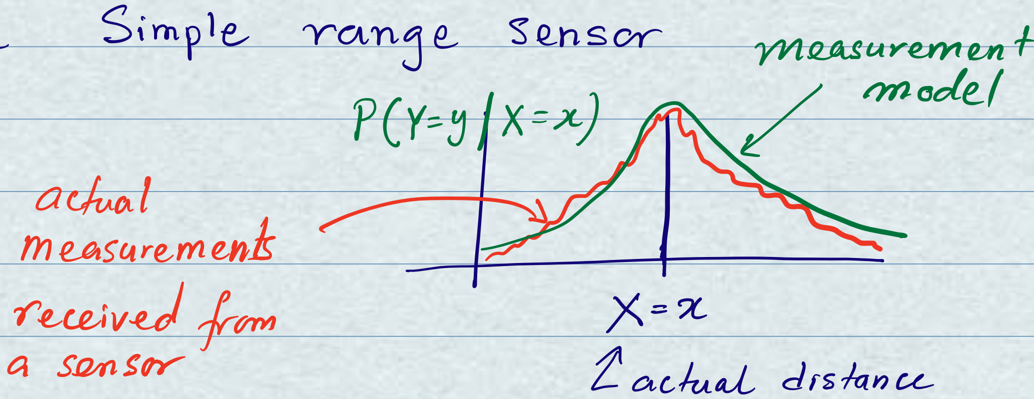
Measurement model

$P(z_t \mid x_{0:t}, z_{1:t-1}, u_{0:t-1})$

We assume $= P(z_t \mid x_t)$

state is complete ↑ measurement model

<u>Example</u> Simple range sensor



<u>Derivation of Bayes filter</u>

Def

Belief is defined as the posterior distribution over state (at time t) given all past measurements and control inputs.
Denoted by $bel(x_t)$

$$bel(x_t) = P(x_t \mid z_{1:t}, u_{1:t})$$

$$= P(\underset{x}{x_t} \mid \underset{y}{z_t} \, \underbrace{z_{1:t-1} \, u_{1:t}}_{z})$$

Using ④

$$= \frac{P(z_t \mid x_t \, z_{1:t-1} \, u_{1:t}) \, P(x_t \mid z_{1:t-1} \, u_{1:t})}{P(z_t \mid z_{1:t-1}, u_{1:t})}$$

$$= \eta \, P(z_t \mid x_t \, z_{1:t-1} \, u_{1:t}) \, P(x_t \mid z_{1:t-1} \, u_{1:t})$$

$$\boxed{bel(x_t) = \eta \, P(z_t \mid x_t) \, \overline{bel}(x_t)}$$

Correction based on measurement

because measurement model assumes state is complete

$\overline{bel}(x_t)$ belief about state at time t before using measurement info at t
but after using control at time t

$$\overline{bel}(x_t) = P(x_t \mid z_{1:t-1}, u_{1:t})$$

Using law of total probability

$$\sum_{x_{t-1}} P(x_t \mid x_{t-1}\ z_{1:t-1}, u_{1:t})\, P(x_{t-1} \mid z_{1:t-1}\ u_{1:t})$$

Using Markov transition model

$$= \sum_{x_{t-1}} P(x_t \mid x_{t-1}, u_t)\, P(x_{t-1} \mid z_{1:t-1}, u_{1:t})$$

IF the control input u_t is chosen randomly (not using x_{t-1})

$$= \sum_{x_{t-1}} P(x_t \mid x_{t-1}, u_t)\, \underbrace{P(x_{t-1} \mid z_{1:t-1}, u_{1:t-1})}_{\text{bet}(x_{t-1})}$$

State transition model

Control input

$$\boxed{\overline{bel}(x_t) = \sum_{x_{t-1}} P(x_t \mid x_{t-1}\ u_t)\, bel(x_{t-1})}$$

prediction based on state transition model and control input u_t

In continuous form

$$\overline{bel}(x_t) = \int_{x_{t-1}} P(x_t \mid x_{t-1}\ u_t)\, bel(x_{t-1})\, dx_{t-1}$$

Algorithm Bayes_filter($bel(x_{t-1}), u_t, z_t$)

Prediction

for all x_t do:

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

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

Correction

end for

return $bel(x_t)$