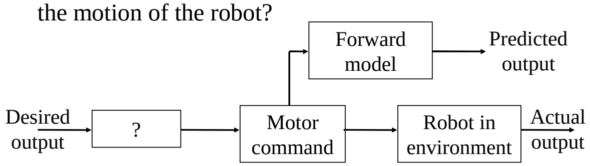
Control 2

Keypoints:

- Given desired behaviour, determine control signals
- Inverse models:
  - Inverting the forward model for simple linear dynamic system
  - Problems for more complex systems
- Open loop control: advantages and disadvantages
- Feed forward control to deal with disturbances

The control problem

- Forward: Given the control signals, can we predict the motion of the robot?



- Inverse: Given the desired motion of the robot can we determine the right control signals?

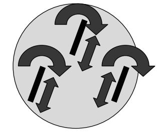
Inverse models

The obvious approach is to invert the forward model.

Simple geometric example – holonomic mobile robot:

- Distance moved for wheel rotation θ:

$$d = \theta \times wheel\ radius$$



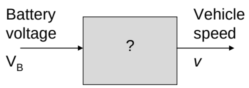
- So to move distance d, rotate wheel by:

$$\theta = \frac{wheel\ radius}{d}$$

Electric Motor

Simple dynamic example –
We have a process model:

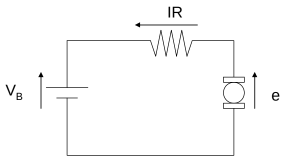
$$V_B = k_1 v + \frac{MR}{k_2}\frac{dv}{dt}$$



Solve to get forward model:

$$v = \frac{V_B}{k_1}\left(1 - \exp\left(\frac{-k_1 k_2}{MR} t\right)\right)$$

- Derivation using Laplace transformation



$$v = \frac{V_B}{k_1}\left(1 - e^{\frac{-k_1 k_2}{MR} t}\right)$$

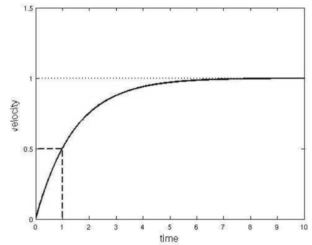
Steady-state: as $t \to \infty$, $e^{\frac{-k_1 k_2}{MR} t} \to 0$, so $v = \frac{V_B}{k_1}$

Half life: solve for t when $v = \frac{V_B}{2k_1}$

$$e^{\frac{-k_1 k_2}{MR} t} = \frac{1}{2}$$

$$\frac{-k_1 k_2}{MR} t = \ln(0.5)$$

$$t \approx -0.7 \times \frac{-MR}{k_1 k_2}$$



Inverse models

Complex example – multilink robot arm forward model:

$$^{R}\mathbf{T}_H = {}^{0}\mathbf{A}_1\, {}^{1}\mathbf{A}_2\, {}^{2}\mathbf{A}_3\, {}^{3}\mathbf{A}_4\, {}^{4}\mathbf{A}_5\, {}^{5}\mathbf{A}_6 = \begin{bmatrix} x_x & y_x & z_x & p_x \\ x_y & y_y & z_y & p_y \\ x_z & y_z & z_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \textbf{(4.93)}$$

where the elements of the matrix are:

$$x_x = C_1[C_{23}(C_4C_5C_6 - S_4S_6) - S_{23}S_5C_6] - S_1(S_4C_5C_6 + C_4S_6) \quad \textbf{(4.94)}$$

$$x_y = S_1[C_{23}(C_4C_5C_6 - S_4S_6) - S_{23}S_5C_6] + C_1(S_4C_5C_6 + C_4S_6) \quad \textbf{(4.95)}$$

$$x_z = S_{23}(C_4C_5C_6 - S_4S_6) + C_{23}S_5C_6 \quad \textbf{(4.96)}$$

$$y_x = C_1[-C_{23}(C_4C_5S_6 + S_4C_6) + S_{23}S_5S_6] - S_1(-S_4C_5S_6 + C_4C_6) \quad \textbf{(4.97)}$$

$$y_y = S_1[-C_{23}(C_4C_5S_6 + S_4C_6) + S_{23}S_5S_6] + C_1(-S_4C_5S_6 + C_4C_6) \quad \textbf{(4.98)}$$

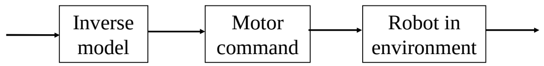
Where $C_1 = \cos\theta_1$, $S_1 = \sin\theta_1$ etc. for joint angles θ_1 to θ_6

Possible, but difficult, to solve for θ_1 to θ_6

Problem

- In general, most robot systems are non-linear.
- Hence, may be difficult to find a solution for the inverse of the forward model.
- There may be no solution.
  - Robot actuator and effector can be designed to ensure solution exists, e.g. Puma vs. humanoid arm
- There may be many solutions.
- There is no general method for finding a solution.

Open loop control

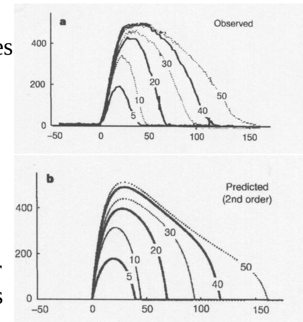


Examples:

- To execute memorised trajectory, produce appropriate sequence of motor torques
- To obtain a goal, make a plan and execute it
  - (means-ends reasoning could be seen as inverting a forward model of cause-effect)
- ‘Ballistic’ movements such as saccades

Saccades

- Humans show highly stereotyped velocity profiles for saccadic movements
- If aim is fastest movement would use ‘bang-bang’ control; but noise is proportional to control signal.
- Actual profiles are well predicted by optimising for end-point accuracy (Harris & Wolpert 1998)

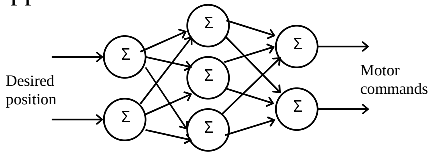


Open loop control

- Potentially cheap and simple to implement e.g. if solution is already known.
- Fast, e.g. useful if feedback would come too late.
- Benefits from calibration e.g. tune parameters of approximate model.
- If model unknown, may be able to use statistical learning methods to find a good fit e.g. neural network.

Neural nets

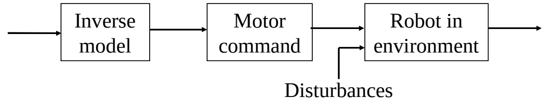
- ANN can be used as non-linear function approximator for the inverse model



- Standard training methods (e.g. back-propagation) can be used to associate target inputs with required control signals

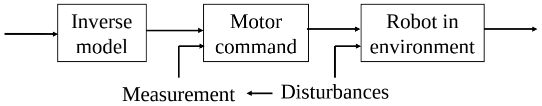
Open loop control

- Neglects possibility of disturbances, which might affect the outcome.



- For example:
  - change in temperature may change the friction in all the robot joints.
  - Or unexpected obstacle may interrupt trajectory

Feed-forward control



- One solution is to measure the (potential) disturbance and use this to adjust the control signals.
- For example
  - thermometer signal alters friction parameter.
  - obstacle detection produces alternative trajectory.

Feed-forward control

- Can sometimes be effective and efficient.
- Requires anticipation, not just of the robot process characteristics, but of possible changes in the world.
- Does not provide or use knowledge of actual output – for this need to use **feedback** control

- see next lecture…

Further reading:

Most standard robotics textbooks (e.g. McKerrow) discuss forward and inverse models in great detail.

For the research on saccades see:

Harris, C.M. & Wolpert, D.M. (1998) Signal dependent noise determines motor planning. *Nature*, 394:780-184.

For an interesting discussion of forward and inverse models in relation to motor control in humans, see: Wolpert, DM & Ghahramani, Z. (2000) “Computational principles of movement neuroscience” Nature Neuroscience 3:1212-1217