Human Motion Control

Lecture 10: Sensory integration
(& Optimal Feedback Control)

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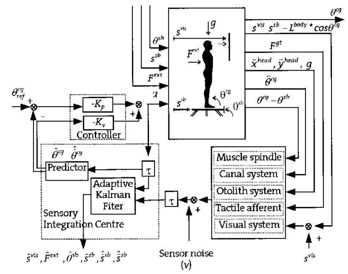
Sensory Integration



Sensory Integration

- Multiple sensors and sensor types provide 'redundant' information
- State variables are 'reconstructed': sensory integration (and are needed for 'optimal' control signals: optimal feedback control)
- Sensor inputs is weighed with expected information and sensor noise
- In case of sensor malfunction, other sensors take over ⇒ Adaptation, or sensory reweighting

Weighting of force and position sensory feedback in humans

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Contents

Sensory weighting

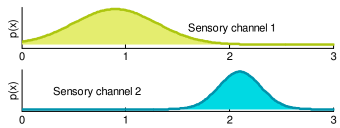
- Balance control
  - Vestibular system
  - Vision
  - Mechanoreceptors
- Haptics
  - Vision
  - Tactile feedback
- Location of one's own body parts in peri-personal space
  - Vision
  - Proprioception

How to integrate multiple sensory inputs to get the most reliable estimate of a sensed variable?

•Van der Kooij et al, Biol Cyb 84, 2001
•Peterka, J Neurophysiol 88(3), 2002
•Körding and Wolpert, Nature 427, 2004

Sensory weighting

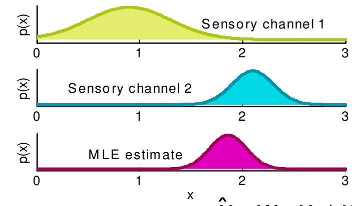
- Problem: estimate a quantity using multiple uncertain sensory channels.
- Image shows the probability density of the true value X, given the measurements from sensor 1 and 2.



- Channel 1 has variance σ_1^2
- Channel 2 has variance σ_2^2
- Question: can channel 1 and 2 be combined such that the overall variance is smaller than σ_1^2 and σ_2^2?

Sensory weighting

- Answer: maximum likelihood estimation (MLE)



- Maximum likelihood estimate: $\hat{X} = W_1 \cdot X_1 + W_2 \cdot X_2$
- Optimal weights: $w_1 = \dfrac{1/\sigma_1^2}{1/\sigma_1^2 + 1/\sigma_2^2}$, $w_2 = 1 - w_1$

Optimal weights

- Proof that the weighted estimate has less variance than each of the separate sensory channels:

$$\sigma^2 = w_1\sigma_1^2 + w_2\sigma_2^2$$

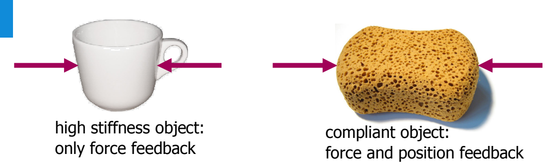
$$w_1 = \frac{1/\sigma_1^2}{1/\sigma_1^2 + 1/\sigma_2^2} \quad , \quad w_2 = \frac{1/\sigma_2^2}{1/\sigma_1^2 + 1/\sigma_2^2}$$

$$\Rightarrow \sigma^2 = \frac{\sigma_1^2\sigma_2^2}{\sigma_1^2 + \sigma_2^2}$$

$$\sigma^2 = \left(\frac{\sigma_2^2}{\sigma_1^2 + \sigma_2^2}\right)\sigma_1^2 < \sigma_1^2$$

$$\sigma^2 = \left(\frac{\sigma_1^2}{\sigma_1^2 + \sigma_2^2}\right)\sigma_2^2 < \sigma_2^2$$

Case study: sensory weighting of force and position feedback

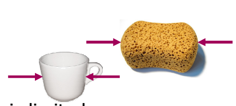


high stiffness object:
only force feedback

compliant object:
force and position feedback

With known stiffness, force can be estimated from position and vice versa through an internal model.

Hypotheses

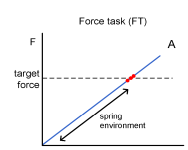


Assumptions:
- Accuracy of sensory feedback is limited.
- Humans can obtain an internal model of object stiffness through training.

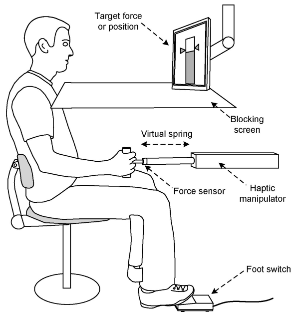
Hypotheses:
- Humans integrate force and position feedback.
- The weight on force feedback increases with stiffness.
- Humans optimally weigh force and position (MLE).

Approach

- Task: reproduce force against a spring.
- In catch trials, spring is replaced by non-linear spring.
- Difference between catch trials and normal trials reveals weighting.
- Repeat for different stiffnesses: reveals weighting strategy



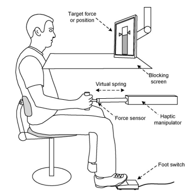
Experimental setup



- Haptic manipulator simulated spring.
- Tasks: reproduce force or reproduce position.
- Visual feedback of force/position.
- Foot switch to indicate on-target

Experimental setup

- Two tasks: force, position
- Four stiffnesses (50, 100, 230, 500 N/m)
- For each stiffness and task:
  - 15 training trials with visual feedback.
  - Alternated blind trials and training trials.
  - 12 catch trials (on average 1 out of 3 blind trials).
- rmANOVA: determine effects of:
  - Trial type (training, normal blind, catch)
  - Stiffness
  - Task



Maximum likelihood model

- Force task

$$F = w_f \cdot \hat{f} + w_x \cdot \left(k \cdot \hat{x}\right)$$

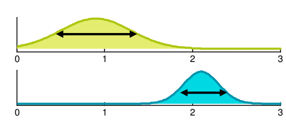
$$w_f^{FT}\left(k\right) = \frac{1/\sigma_f^2}{1/\sigma_f^2 + 1/\left(k^2 \cdot \sigma_x^2\right)}$$

$$w_x^{FT}\left(k\right) = \frac{1/\left(k^2 \cdot \sigma_x^2\right)}{1/\sigma_f^2 + 1/\left(k^2 \cdot \sigma_x^2\right)}$$

- No fundamental difference between force and position task!
- Two parameters: variance of position and force feedback.

Maximum likelihood model

- Determine variance of position and force feedback in separate experiment (infinite stiffness and zero stiffness).
- Determine optimal weights between force and position.
  - for different tasks: force task and position task.
  - for different stiffnesses.



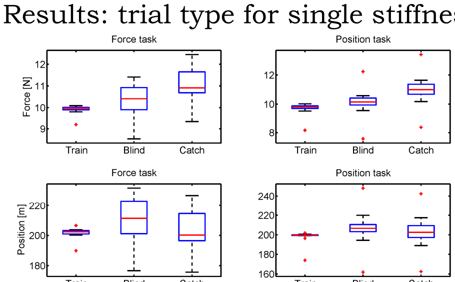
Maximum likelihood model

- Difference between normal blind trials and catch trials
  - Determine optimal weights for linear spring with spring constant k.
  - Solve force / position for non-linear spring.

$$\begin{cases} F = w_f^{FT} \cdot \hat{f} + w_x^{FT} \cdot k \cdot \hat{x} \\ \hat{f} = \left(k + \delta_f \cdot k^2 / f_{target} \cdot \hat{x}\right) \cdot \hat{x} \end{cases}$$

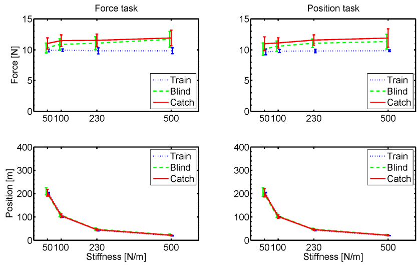
$$\begin{cases} X = w_f^{PT} \cdot \hat{f} / k + w_x^{PT} \cdot \hat{x} \\ \hat{f} = \left(k + \delta_f \cdot k^2 / f_{target} \cdot \hat{x}\right) \cdot \hat{x} \end{cases}$$

Results: trial type for single stiffness



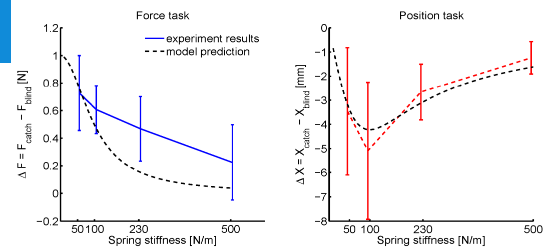
- Forces higher in blind trials and catch trials
- Evidence of sensory integration

Results: stiffness effect



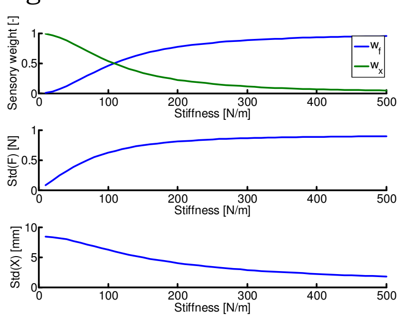
- No task effect.
- Significant effect of trial type and stiffness.

Results: difference blind–catch trials



- Model parameters: σ_f=0.92 N, σ_x=8.5 mm
- Trends show weighting between force and position feedback.
- MLE model follows these trends, but overestimates force feedback.

Weights as function of stiffness



Discussion

- Significant effect of stiffness: subjects weighted sensory feedback according to object stiffness.
- Increased stiffness, increased weight on force feedback.
- Assumption: weights did not change during catch trials. Subjects could not distinguish catch trials from blind trials.
- Model predicted no task effect. No task effect was found experimentally. Interpretation: "Just do the same"
- MLE model explains course of data well, but subjects seem to be more biased towards position feedback.

Conclusion

- Experimental setup could discriminate between modalities force and position within the proprioceptive system.
- Humans integrate and weigh force and position feedback.