Human Motor Control

(how the Central Nervous System plans motion)

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I got this information from two classes:

- Kinesiology 533: Neuromechanics
  - Interaction of the nervous and musculoskeletal systems during human/animal movement
  - Taught by Dan Ferris (now a professor at University of Florida)

- Mechanical Engineering 646: Mechanics and Control of Human Movement
  - Locomotor mechanics and design/control of wearable robotic systems
  - Taught by Elliott Rouse
  - In particular, a guest lecture in this class by his postdoc Tyler Clites
  - I will also use a Simulink example developed by Tyler!
What’s going on behind the scenes to make this happen?
Robotic control hierarchy

High-level
What is the task that we want Atlas to do?

Mid-level
What are the joint dynamics that Atlas needs to accomplish it?

Low-level
How do we deliver the appropriate amount of current to Atlas’ motors to produce those dynamics?
The same control aspects are important for human motion

(Katelyn Ohashi, UCLA Athletics, 2019)
Human control hierarchy

- **High-level**
  - What task do I want to do?

- **Mid-level**
  - What are the joint dynamics that I need to accomplish it?

- **Low-level**
  - How do I deliver the appropriate activations to my muscles to produce those dynamics?
Why do we care about how humans plan motion?

Science

Rehabilitation

Wearable Robots

[appreciategoods.com]  [aayushman.in]  [news.engin.umich.edu]
Quick background: Central Nervous System (CNS)

- Primary processing unit
  - High-level task planning
  - Volitional control

- Secondary, distributed processing unit
  - Low-level execution
  - Reflexive control
Quick background: Central Nervous System (CNS)

Brain

Spinal Cord

“"I want to touch that glowing red thing""

RUN AWAY, RUN AWAY!

[Images from Tyler Clites’ presentation]
Quick background: Muscle Activation

CNS \rightarrow Neural Signal \rightarrow Activation Processes \rightarrow Muscle Contraction \rightarrow Physical Joint Motion
Quick background: Afferent and efferent neurons

Afferent neurons carry nerve impulses from sensory organs to the CNS

Efferent neurons carry nerve impulses from CNS to muscles
Outline of our human motor control topics

- Low-level control
  - Feedforward
  - Feedback
  - Hybrid FF+FB
- Mid-level control
  - Inverse Kinematics and Inverse Dynamics
  - Equilibrium Point Hypothesis
  - Muscle Synergies
  - Internal Models
  - Uncontrolled Manifold Hypothesis
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We’ll use a pendulum example for low-level control

this looks enough like a human leg...right?
We’ll use a pendulum example for low-level control

dynamic equation of motion:

\[ u = J \ddot{\theta} + b \dot{\theta} + k \theta \]
We’ll use a pendulum example for low-level control

\[ u = J \ddot{\theta} + b \dot{\theta} + k \theta \]

[\text{Kuo A., Motor Control, 2002}]

Basically, we know how this pendulum will respond to a given input \( u \).
Feedforward (open-loop) control

A movement is “launched” at some target, and can’t be corrected after.
Ingredients of feedforward control

\[(\theta, \dot{\theta}, \ddot{\theta})_{goal}\]  
controller  
\[u\]  
pendulum physics  
\[(\theta, \dot{\theta}, \ddot{\theta})_{real}\]  

\[u = J\ddot{\theta} + b\dot{\theta} + k\theta\]

*Apply 5 NM of torque for 3 seconds!*
Feedforward control - Simulink demo

[Simulink demo created by Tyler Clites]
Feedforward control - Simulink demo takeaways

Benefits:
No dependence on sensor accuracy

Pitfalls:
Sensitive to torque disturbance and timing errors
Feedback (closed-loop) control

A feedback system constantly monitors its own progress and adjusts its control accordingly.
Ingredients of feedback control

APPLY TORQUE TO REDUCE ERROR BETWEEN CURRENT STATE AND GOAL!

controller

desired kinematics

\((\theta, \dot{\theta}, \ddot{\theta})_{\text{goal}}\)

torque

\(u\)

\[ u = J\ddot{\theta} + b\dot{\theta} + k\theta \]

pendulum physics

joint (or pendulum) state

\((\theta, \dot{\theta}, \ddot{\theta})_{\text{real}}\)

sensors

\((\theta, \dot{\theta}, \ddot{\theta})_{\text{measured}}\)
Feedback control - Simulink demo
Feedback control - Simulink demo takeaways

Benefits:
No dependence on timing, robust to torque disturbance

Pitfalls:
Sensitive to measurement error in sensors
Could a hybrid FF + FB approach be the best of both worlds?
Feedforward + feedback control - Simulink demo
### Summary of low-level control

<table>
<thead>
<tr>
<th></th>
<th>Torque Disturbance</th>
<th>Timing Disturbance</th>
<th>Sensor Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedforward</td>
<td>❌</td>
<td>❌</td>
<td>✅</td>
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<tr>
<td>Feedback</td>
<td>✅</td>
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<tr>
<td>Hybrid</td>
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</table>
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Inverse kinematics

We are jointed \((\theta_1, \theta_2)\) beings in a Cartesian \((x, y)\) world

\[ x = l_1 \cos(\theta_1) + l_2 \cos(\theta_1 + \theta_2) \]
\[ y = l_1 \sin(\theta_1) + l_2 \sin(\theta_1 + \theta_2) \]

SOLVE FOR THE JOINT ANGLES (AND ANGULAR VELOCITIES) NEEDED TO ARRIVE AT GOAL!
Experiment where inverse kinematics theory falls short

[Lackner, J.R. and Dizio, P., J. Neurophysiology, 1994]
Inverse dynamics

Similar, but with torques and forces

\[
\tau_1 = \theta_1 \left( l_1 + l_2 + m_2l_1 \cos \theta_2 + \frac{m1l_1^2 + m_2l_2^2}{4} \right) \\
+ \theta_2 \left( l_3 + \frac{ml_2}{2} \cos \theta_2 + \frac{ml_2^2}{4} \right) \\
- \theta_2 \frac{ml_2}{2} \sin \theta_2 - \theta_1 \theta_2 m_2l_1 \sin \theta_2 \\
+ g \left( \frac{ml_2}{2} \cos \theta_1 + \theta_2 \right) + l_1 \left( \frac{m_1}{2} + m_2 \right) \cos \theta_1
\]

\[
\tau_2 = \theta_1 \left( l_3 + \frac{ml_2}{2} \cos \theta_2 + \frac{ml_2^2}{4} \right) + \theta_2 \left( l_3 + \frac{ml_2}{2} \right) \\
+ \theta_2 \frac{ml_2}{2} \sin \theta_2 + g \frac{ml_2}{2} \cos \theta_1 + \theta_2
\]

desired motion pattern \((\theta_1, \theta_2)_{goal}\)

inverse dynamics

joint torques \((\tau_1, \tau_2)\)

forward dynamics

actual motion pattern \((\theta_1, \theta_2)_{real}\)
Equilibrium Point Hypothesis

Main idea: when we identify a goal for our end effector (e.g., reaching our hand to a desired location), we set an equilibrium point for our joints. If we’re perturbed, we will settle back on the equilibrium point.

spring equilibrium position

elongated

compressed

[Image adapted from examfear.com]
Deafferented monkeys without visual feedback can still move to a desired target, even when a disturbance is applied.

**FIG. 1.** Monkey set up in arm apparatus. Arm is strapped to splint, which pivots at elbow. Target lights are mounted in perimeter arc at 5° intervals. During experimental session, the monkey was not permitted to see its arm, and the room was darkened.
EPH doesn’t hold up for the rotating room experiment...

Muscle Synergies

controlling each wheel separately vs. reducing degrees of freedom by coordinating wheels as a group
control can be simplified by grouping muscles into functional units
Muscle Synergies - cool frog experiment

stimulate one area of the spinal cord...

...and the entire frog leg moves!

[Bizzi, E. et al., Science, 1991]
Muscle Synergies - viewpoints depending on field

**MUSCLE SYNERGIES ARE AWESOME!**
HUMANS HAVE FOUND A WAY TO EFFECTIVELY RECRUIT MUSCLES BY REDUCING DEGREES OF FREEDOM.

**MUSCLE SYNERGIES ARE Frustrating.** THEY MAKE IT DIFFICULT FOR STROKE PATIENTS TO UNCOUPLE GROUPS OF MUSCLES.
Muscle Synergies - EMG decomposition

Temporal components \(c_1, c_2, c_3\) x Weights \(w_1, w_2, w_3\) = Muscle activations \(m_1, m_2, m_3, m_4, m_5\)
Muscle Synergies - EMG decomposition

- EMG from stroke patients needed fewer components
- EMG from children needed fewer components than EMG from adults

[Text excerpt from Cappellini, G. et al., J. Neurophysiology, 2006]
Internal Models
Internal Models

Internal Models - supporting experiment

Subjects manipulate this handle to specified targets.

Handle trajectories when no disturbance is applied.

Internal Models - supporting experiment

then, a force field is applied to the handle...

initial handle trajectories when force field is applied

B, Forces acting on the hand while making reaching movements in the left workspace of Figure 2 from the center to targets about the circumference of a circle. Movements are simulated as being minimum jerk with a period of 0.5 sec and amplitude of 10 cm.

Internal Models - supporting experiment

improvement (updating internal model) over time...

Internal Models - supporting experiment

when the force field was removed...

...subjects had to train themselves the opposite way!

Uncontrolled Manifold Hypothesis

large variability in joint angles and velocities

Small variability in where the hammer lands
Uncontrolled Manifold Hypothesis

- The nervous system controls some degrees of freedom (DOFs), but may care less about other DOFs.
- This hypothesis states that the variance within a given task is confined to a subspace of DOFs that can preserve task performance.
- The subspace is called the uncontrolled manifold (UCM).
- Example UCM: During sit-to-stand, all combinations of lower-limb joint angles that together place the center of mass in a certain position.

[Scholz, J.P. and Schöner, G., Exp. Brain Research, 1999]
In conclusion…. Science is hard!!

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So many cool experiments about human/animal motor control, so many different ways to interpret them…