Systems Neuroscience  
CISC 3250

Motor control

Professor Daniel Leeds  
dleeds@fordham.edu  
JMH 332

Classes of motion

- **Voluntary**
  - Somatic
    - Skeletal muscle
  - Autonomic
    - Sympathetic
      - Fight or Flight
    - Parasympathetic
      - Resting state
    - Smooth muscle
    - Cardiac muscle

Classes of motion

Pathways to motion in (typically)  
2 synaptic steps

0 Command from primary motor cortex (M1)  
1 Synapse onto neuron in spinal cord/cranial nerve  
2 Synapse onto muscle

**Efferent** – motor message out  
**Afferent** – perceptual message in

Cortical commands sent to contralateral side of body

Precise motion in an imprecise world

Imprecise neurons
- Efferent signal for motion will present variable number of NT molecules per spike
- Number of spikes may vary between movement repetitions

Unreliable world
- Wind blows while you pick up a bag
- You trip on unseen object while walking

![Probability graph](NT_release_spike.png)
Monitoring body motion

- Seeing body move (covered in later lecture)
- Skin stretch
- Muscle stretch/contraction – muscle spindles

- Head rotations – inner ear; semi-circular canals
  Anterior: Sagittal spin  Posterior: Coronal spin  Horizontal: Axial spin

Adjusting motion with the cerebellum

- Compare motor commands to actual motion
- Cerebellar inputs:
  – Climbing fiber from Inferior Olive (brainstem)
  – Mossy fiber from Spinal cord, Brainstem
- Cerebellar outputs:
  – Purkinje cells – inhibition to brainstem

Vestibular system

Three canals on left and right side of head: anterior, posterior, horizontal

1. Head rotates
2. Fluid flows
3. Hairs displaced

Control theory

Correcting errors in motion

Motor command generator  Motor command  Controlled object  Actual state  Sensory system

Afferant – muscle sensors
Re-afferant – visual sensors
Motor command generation

swing leg forward -> rotate leg using muscle force

Motion with basic feedback system

\[
\text{Move} = \frac{1}{2} \times (\text{Target} - \text{Current})
\]

Target: 5

\[
t=1 \text{ Start at 0}
\]

Motion strategy

<table>
<thead>
<tr>
<th>time</th>
<th>Sense</th>
<th>Move</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>t=1</td>
<td>0</td>
<td>+2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>t=2</td>
<td>2.5</td>
<td>+1.25</td>
<td>3.75</td>
</tr>
<tr>
<td>t=3</td>
<td>3.75</td>
<td>+.63</td>
<td>4.38</td>
</tr>
<tr>
<td>t=4</td>
<td>4.38</td>
<td>+.31</td>
<td>4.69</td>
</tr>
<tr>
<td>t=5</td>
<td>4.69</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Actual\(_t\) = Actual\(_{t-1}\) + Move\(_{t-1}\)

Sense\(_t\) = Actual\(_{t-1}\) delay
Motion with basic feedback system

Motion strategy

\[ \text{Move} = \frac{1}{2} \times (\text{Target} - \text{Sensed}) \]

<table>
<thead>
<tr>
<th>t=1</th>
<th>t=2</th>
<th>t=3</th>
<th>t=4</th>
<th>t=5</th>
<th>t=6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sense: 0</td>
<td>0</td>
<td>0</td>
<td>2.5</td>
<td>5</td>
<td>7.5</td>
</tr>
<tr>
<td>Move: +2.5</td>
<td>+2.5</td>
<td>+2.5</td>
<td>+1.25</td>
<td>0</td>
<td>-1.25</td>
</tr>
<tr>
<td>Actual: 0</td>
<td>2.5</td>
<td>5</td>
<td>7.5</td>
<td>8.75</td>
<td>8.75</td>
</tr>
</tbody>
</table>

Target: 5
t=1 Start at 0
2 time point sensation delay

Delay-based Oscillations

- If sense delay and update fraction \( \frac{1}{2} \times (\text{Targ-Sens}) \) are small, oscillations will converge to target
- If sense delay and/or update fraction \( \frac{1}{2} \times (\text{Targ-Sens}) \) are large, oscillations will get larger and NOT converge to target

Simulating in Matlab

```matlab
target=5;
actual(1)=0;
actual(2)=0;
actual(3)=0;
sens(3)=actual(1);
mov=0.5*(target-sens(3));
actual(4)=actual(3)+mov;
sens(4)=actual(2);
mov=0.5*(target-sens(4));
actual(5)=actual(4)+mov;
... sens(31)=actual(29);
mov=0.5*(target-sens(31));
actual(32)=actual(31)+mov
```
Simulating in Matlab

target=5;
actual(1)=0;
actual(2)=0;
actual(3)=0;
for n=3:31,
sens(n)=actual(n-2);
mov=0.5*(target-sens(n));
actual(n+1)=actual(n)+mov;
end;

Expanded control theory

Challenge: Waiting for afferent feedback is slow

Solutions:
- Anticipate typical motion progress – forward model
- Account for typical motion progress from the beginning – inverse model

Forward model

\[ \text{Move} = \frac{1}{2} \times (\text{Target-Forward-(Sensed-Delay)}) \]

- Forward: Adjust motion based on predicted position
- Delay: Predicted motion with time delay
- Sense: Adjust predicted error based on actual position
- Adjust models (over longer experience)
Motion strategy

\[ \text{Move} = \frac{1}{2} \times (\text{Target} - \text{Forward} - (\text{Sensed} - \text{Delay})) \]

<table>
<thead>
<tr>
<th>t=1</th>
<th>t=2</th>
<th>t=3</th>
<th>t=4</th>
<th>t=5</th>
<th>t=6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sense</td>
<td>0</td>
<td>0</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forward</td>
<td>0</td>
<td>2.5</td>
<td>3.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delay</td>
<td>0</td>
<td>0</td>
<td></td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Actual</td>
<td>0</td>
<td>2.5</td>
<td>3.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Move</td>
<td>+2.5</td>
<td>+1.25</td>
<td>+0.625</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Target: 5

\( t=1 \) Start at 0

2 time point sensation delay

Forward_, Forward\_t-1 + Move\_t-1

Delay, Delay\_t-delay

Actual, Actual\_t-1 + Move\_t-1

Motion with forward model + push

- Desired state
- Motor command generator
- Motor command
- Controlled object
- Actual state
- Sensory system
- Disturbance
- Forward model
- Sensory model

Motion strategy

\[ \text{Move} = \frac{1}{2} \times (\text{Target} - \text{Forward} - (\text{Sensed} - \text{Delay})) \]

<table>
<thead>
<tr>
<th>t=1</th>
<th>t=2</th>
<th>t=3</th>
<th>t=4</th>
<th>t=5</th>
<th>t=6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sense</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>Forward</td>
<td>0</td>
<td>2.5</td>
<td>3.75</td>
<td>4.38</td>
<td>4.69</td>
</tr>
<tr>
<td>Delay</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>Actual</td>
<td>0</td>
<td>2.5</td>
<td>3.75</td>
<td>4.38</td>
<td>4.69</td>
</tr>
<tr>
<td>Move</td>
<td>+2.5</td>
<td>+1.25</td>
<td>+0.63</td>
<td>+0.31</td>
<td>+0.16</td>
</tr>
</tbody>
</table>

Target: 5

\( t=1 \) Start at 0

2 time point sensation delay

Forward, Forward\_t-1 + Move\_t-1

Delay, Delay\_t-delay

Compare model motion and actual motion after 2 time step delay

Disturbance

Moved by +2.5
Pushed by +2
Moved by +0.63
Moved by +0.62/2/2

Act | 0 | 4.5 | 5.75 | 6.38 |
For | 0 | 2.5 | 3.75 | 4.38 |
Sen | 0 | 0 | 0 | 4.5 |
Del | 0 | 0 | 0 | 2.5 |
Mov | +2.5 | +1.25 | +0.625 | -0.69 |

Compare model motion and actual motion after 2 time step delay

Move = 1/2 x (Target Forward - (Sensed Delay))
desired location = 5  
starting location = 0  
sensory delay = 2  
push forward by 2 at time 1  
no other

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>F</th>
<th>S</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.5</td>
<td>2.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>5.75</td>
<td>3.75</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>6.38</td>
<td>4.38</td>
<td>4.5</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>5.7</td>
<td>4.7</td>
<td>5.75</td>
<td>3.75</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>4.7</td>
<td>5.75</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5.7</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Compare model motion and actual motion after 2 time step delay

Motor learning biology: basal ganglia

Striatum  
- Putamen  
- Caudate nucleus  
Globus pallidus  
Substantia nigra  
Sub-thalamic nucleus (STN)

Basal Ganglia and Related Structures of the Brain

Striatum

- Putamen
- Caudate nucleus
Globus pallidus
Substantia nigra
Sub-thalamic nucleus (STN)

Basal Ganglia and Related Structures of the Brain

Striatum

- Putamen
- Caudate nucleus
Globus pallidus
Substantia nigra
Sub-thalamic nucleus (STN)

Basal Ganglia and Related Structures of the Brain

Striatum

- Putamen
- Caudate nucleus
Globus pallidus
Substantia nigra
Sub-thalamic nucleus (STN)