Optimization of the behavior system for controlling bipedal locomotion against external disturbances

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Outline

- Overview Behavior-Based Control Architecture
- Disturbance Estimation and Compensation while Standing
- Strategies for Push Recovery while Walking
Overview Behavior-Based Control Architecture
Behavior-Based Control Architecture

[Proetzsch10, Luksch10]
Disturbance Estimation and Compensation (DEC) while Standing
Disturbance Estimation and Compensation (DEC)

[Frame Diagram]

[Mergner10]
DEC – Implementation/Integration
DEC - Experiments

[Images of DEC experiments showing different stages of movement]
DEC - Results

Support Surface Rotating at 0.6Hz, ±6° Amplitude
Support Surface Rotating at 0.1Hz, ±2° Amplitude, ±0.2° Random Offset
Strategies for Push Recovery while Walking
Push Recovery - Detection

[Hof05, Hof08]
Push Recovery - Strategies

- **Hip and Ankle Strategy**
  - If push is detected when both legs in ground contact.
  - Additional torque on hip and ankle joint of the leg next to leave ground.

- **Knee Strategy**
  - If push is detected during swing phase or weight acceptance.
  - Stiffness and equilibrium point of knee joint are modulated.
Push Recovery - Experiments
Push Recovery – Results Hip Ankle Strategy
Push Recovery – Results Knee Strategy
Conclusion

- In General:
  - Further mechanisms/principles identified in biology, neuroscience and biomechanics can be easily integrated.
  - Behavior network can be extended and optimized.
- DEC
  - Applied to one joint – extension to multiple joints?
- Push recovery
  - Only sagittal disturbances – strategies for lateral pushes?
References

Thank you for your attention!
Joint Control Simulated Biped
Reflex Controllers

- Local reflexes:
  - feedback mechanism
  - kinematic event-based triggering

- Postural reflexes:
  - Supraspinal reflexes and more complex than local feedback
  - estimation of upper body orientation
  - calculation of CoM and XcoM
  - foot placement and velocity correction.
Postural Reflexes – Upright Trunk

- Body stabilization in frontal plane
- Cascaded position-velocity controller
- Modulated by ground contact
Postural Reflexes – Forward Velocity

- Calculates correction value to generate ankle torque about y-axis
- Trajectory of $x_{com_x}$ is compared to an approximation – sine wave:

$$x_{com_x, \text{target}} = v_{\text{target}} \left[ x_{com_x, \text{start}} + (x_{com_x, \text{end}} - x_{com_x, \text{start}}) \sin \left( \frac{\pi}{2} t \right) \right]$$
Postural Reflexes – Lateral Stability

- Trajectory of $x_{com_y}$ is compared to an approximation – fourth order polynomial:

$$com_{y,\text{target}} = v_{\text{target}} \left[ com_{y,\text{start}} + (com_{y,\text{end}} - com_{y,\text{start}}) \left( 1 - (2t - 1)^4 \right) \right]$$

- Lateral Balance Ankle
  - Calculates correction value to generate ankle torque about $x$-axis

- Lateral Foot Placement
  - Uses correction value to adapt hip angle during leg swing
Motor Patterns

- feed-forward control
- analysis of muscle activities and kinetic data

\[
\hat{\tau} = \begin{cases} 
\frac{1}{2} + \frac{1}{2} \sin \left( \pi \left( \frac{t}{T_1} - \frac{1}{2} \right) \right) & \text{for } 0 \leq t < T_1 \\
1 & \text{for } T_1 \leq t < T_2 \\
\frac{1}{2} - \frac{1}{2} \sin \left( \pi \left( \frac{t-T_2}{T_3-T_2} - \frac{1}{2} \right) \right) & \text{for } T_2 \leq t \leq T_3 
\end{cases}
\]
Phases of Walking

1. Weight acceptance
2. Propulsion
3. Stabilization
4. Leg swing
5. Heel strike

- Right leg:
  - 1. Weight acceptance
  - 2. Propulsion
  - 3. Stabilization
  - 5. Heel strike

- Left leg:
  - 3
  - 4
  - 5

- Foot phases:
  - Full contact
  - Toe-off
  - Locked knee
  - Full contact
Walking Phase 1: Weight Acceptance

1. Weight Accept.
2. Propulsion
3. Trunk Stabilization
4. Leg Swing
5. Heel Strike

Lower Trunk
- Stabilize Pelvis L

Left Leg
- Weight Accept.
- Forward Velocit. L
- Upright Trunk L
- Lat. Bal. Ankle L
Walking Phase 1: Weight Acceptance

- **Motor Pattern**: to control knee joint to guarantee a smooth weight acceptance.
- **Local Reflexes**: to stabilize the pelvis about the x-axis.
- Other joints of upper trunk passively controlled.

- **Postural Reflexes**: to aim for suitable forward velocity, posture of upper trunk and lateral stabilization
Walking Phase 2: Propulsion

1. Weight Accept.
2. Propulsion
3. Trunk Stabiliz.
4. Leg Swing
5. Heel Strike

Lower Trunk
- Stabilize Pelvis L
- Initialize Swing L

Left Leg
- Forward Velocit. L
- Upright Trunk L
- Lat. Bal. Ankle L
- Leg Propel
Walking Phase 2: Propulsion

- **Motor Pattern:** to create a plantarflexion of ankle.
- **Motor Pattern:** to start leg swing.
- **Local Reflexes:** to stabilize the pelvis.
- **Postural Reflexes:** to aim for suitable forward velocity, posture of upper trunk and lateral stabilization.
Walking Phase 3: Stabilization
Walking Phase 3: Stabilization

- **Motor Pattern:** to push body forward.
- **Motor Pattern:** to continue leg swing.
- **Motor Pattern:** to swing the arm.
- **Motor Pattern:** to move the CoM to the stance leg.
- **Postural Reflexes:** to erect the upper trunk.
Walking Phase 4: Leg Swing
Walking Phase 4: Leg Swing

- **Motor Pattern**: to continue leg swing.

- **Motor Pattern**: to swing the arm.

- **Local Reflexes**: to stretch the knee joint.

- **Local Reflexes**: to establish ground clearance.

- **Local Reflexes**: to achieve a suitable angle of attack at heel strike.

- **Postural Reflexes**: to adapt hip angle during swing phase.
Walking Phase 5: Heel Strike
Walking Phase 5: Heel Strike

- **Motor Pattern**: to keep knee stiff.

- **Local Reflexes**: to prevent hip from overswinging.

- **Local Reflexes**: to generate a damping torque to soften foot plantarflexion.

- **Postural Reflexes**: to adapt hip angle to land the foot suitably.
Scaling of Biped I

<table>
<thead>
<tr>
<th>Size</th>
<th>1.8m</th>
<th>1.52m</th>
<th>1.26m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>78kg</td>
<td>58kg</td>
<td>40kg</td>
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<tr>
<td>DoFs</td>
<td>21</td>
<td>21</td>
<td>21</td>
</tr>
</tbody>
</table>

Biped 1.8m

Biped 1.52m

Biped 1.26m
Scaling of Biped II

- Courses of torques during one gait cycle

- 1.8m
- 1.5m
- 1.2m
Scaling of Biped III

- Courses of power during one gait cycle

1.8m
1.5m
1.2m
## Scaling of Biped IV

- Comparison of torques and power

<table>
<thead>
<tr>
<th>Joint</th>
<th>Peak Torque [Nm]</th>
<th>Maximum Power [W]</th>
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<tbody>
<tr>
<td></td>
<td>1.2m</td>
<td>1.5m</td>
</tr>
<tr>
<td>Spine Y</td>
<td>55.0</td>
<td>66.8</td>
</tr>
<tr>
<td>Hip X</td>
<td>50.7</td>
<td>99.3</td>
</tr>
<tr>
<td>Hip Y</td>
<td>89.5</td>
<td>116.8</td>
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<tr>
<td>Hip Z</td>
<td>12.1</td>
<td>19.2</td>
</tr>
<tr>
<td>Knee Y</td>
<td>42.6</td>
<td>51.2</td>
</tr>
<tr>
<td>Ankle X</td>
<td>7.9</td>
<td>7.3</td>
</tr>
<tr>
<td>Ankle Y</td>
<td>31.5</td>
<td>44.2</td>
</tr>
</tbody>
</table>
Conclusion of Scaling Biped

- Most existing control units suitable for different sizes of biped
- Joints in frontal plane critical for lateral stability
- Less robustness of stability requiring more control efforts
- More flexible learning controller required
Integration of Impulsive Control

- Feed-forward control units replaced by impulsive control
- Convenient for learning control
- Combination of time- and event-based control
Thank you for your attention!
Introduction of iB2C, MCA2 and Finroc
Framework
Finroc Structure

**Plugins**
- ib2c (1.3 kSLOC)
- blackboard (1.8 kSLOC)
- structure (820 SLOC)
- runtime_construction (2.1 kSLOC)
- scheduling (567 SLOC)
- parameters (1.8 kSLOC)
- data_ports (5.8 kSLOC)
- rpc_ports (1.7 kSLOC)

**Core**
- core (3.8 kSLOC)

**RRLIBS**
- buffer_pools (576 SLOC)
- concurrent_containers (2.1 kSLOC)
- rtti (1.9 kSLOC)
- thread (1.5 kSLOC)
- serialization (3.1 kSLOC)
- logging (1.4 kSLOC)
- time (692 SLOC)
- xml (670 SLOC)
- design_patterns (790 SLOC)
- util (899 SLOC)
**Basic Sense/Control Module**

- Modules have inputs and outputs called Ports
- Ports can be any type (serializable)
Data Flow Interconnection

- 2 half-cycles: Sense() and Control()
- 1 source to many targets, at most one source per target
- “Directionless” modules available
Finstruct Example
Simulation: SimVis3D

- All robots have simulation counterpart
- Identical interface for hardware abstraction and simulation → control program does not know if on real machine
- Finroc modules allow very high level of abstraction
- Simulation of pressures, engine currents, sensor noise
Integrated Behavior-based Control IB²C

- Input vector $\vec{e}$, output vector $\vec{u}$
- Stimulation $s$, inhibition vector $\vec{i}$
- Activity vector $\vec{a}$, target rating $r$
- Transfer function $\vec{u} = F(\vec{e}, \vec{i})$
Interaction

- Follow object & Avoid collision
- “Turn to object”
  - stimulated by “Follow object”
  - inhibited by “Avoid collision”
- Fusion: Weighted average