BALANCING AND ACTIVE SENSING USING WHOLE-BODY CONTROL FRAMEWORK

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BALANCING AND ACTIVE SENSING

- Using the whole-body control framework based on the operational space control framework
  - More experimental aspects

Balancing  Active Sensing for Terrain
DESIGN CONCEPT FOR BIPED ROBOT

- Integrate Design and Frame
  + Open design allows airflow and accessibility
- Unique
- Suggest human proportions, not replicate humans
  + Human-like motion requires human-like design
  + Not making androids
- Torque capability similar to human
- Back-drivability for compliance motion
PROCESS: SIMULATION

- Weight 71.295 KG
  + Upper 30.05 KG
  + Lower 40.245 KG

- Squat
  + 141° Knee Bend
  + 1 sec

- Walking
  + 0.1, 0.2, 0.3 m/sec
  + Single Support 0.3 sec
  + Double Support 0.7 sec

### Squat Simulation

<table>
<thead>
<tr>
<th>Joint</th>
<th>Peak torque (Nm)</th>
<th>Peak velocity (rad/sec)</th>
<th>RMS torque (Nm)</th>
<th>RMS velocity (rad/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>3</td>
<td>27.030</td>
<td>2.594</td>
<td>11.205</td>
<td>0.832</td>
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<td>4</td>
<td>182.816</td>
<td>4.916</td>
<td>85.094</td>
<td>2.491</td>
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<tr>
<td>5</td>
<td>24.027</td>
<td>3.286</td>
<td>10.053</td>
<td>1.135</td>
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<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</table>

### Walking Simulation

<table>
<thead>
<tr>
<th>Joint</th>
<th>Peak torque (Nm)</th>
<th>Peak velocity (rad/sec)</th>
<th>RMS torque (Nm)</th>
<th>RMS velocity (rad/sec)</th>
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<tbody>
<tr>
<td>1</td>
<td>53.944</td>
<td>0.811</td>
<td>16.869</td>
<td>0.187</td>
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<td>2</td>
<td>91.258</td>
<td>0.497</td>
<td>46.224</td>
<td>0.252</td>
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<td>3</td>
<td>178.823</td>
<td>2.536</td>
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<td>86.952</td>
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<td>48.540</td>
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<td>5</td>
<td>114.165</td>
<td>2.043</td>
<td>30.220</td>
<td>0.780</td>
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<td>6</td>
<td>24.255</td>
<td>0.628</td>
<td>6.562</td>
<td>0.231</td>
</tr>
<tr>
<td>Joint Number</td>
<td>Hip Yaw</td>
<td>Hip Roll</td>
<td>Hip Pitch</td>
<td>Knee Pitch</td>
</tr>
<tr>
<td>--------------</td>
<td>---------</td>
<td>----------</td>
<td>-----------</td>
<td>------------</td>
</tr>
<tr>
<td>Motor Name</td>
<td>Kollmorgen RBE(H) 01811 C</td>
<td>Kollmorgen RBE(H) 01812 C</td>
<td>Kollmorgen RBE(H) 01813 C</td>
<td>Kollmorgen RBE(H) 01813 C</td>
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<tr>
<td>Max Cont. Output Power (W)</td>
<td>300</td>
<td>364</td>
<td>427</td>
<td>427</td>
</tr>
<tr>
<td>Cont. Torque (N-m)</td>
<td>0.856</td>
<td>1.220</td>
<td>1.54</td>
<td>1.54</td>
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<tr>
<td>Peak Torque (N-m)</td>
<td>3.04</td>
<td>4.62</td>
<td>6.15</td>
<td>6.15</td>
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<tr>
<td>Speed @ 48V (RPM)</td>
<td>3780</td>
<td>2500</td>
<td>2927</td>
<td>2927</td>
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<tr>
<td>Reduction Ratio</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
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<tr>
<td>Cont. Torque after reduction (N-m)</td>
<td>42.8</td>
<td>61.0</td>
<td>77.0</td>
<td>77.0</td>
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<tr>
<td>Peak Torque after reduction (N-m)</td>
<td>152.0</td>
<td>231.0</td>
<td>307.5</td>
<td>307.5</td>
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<tr>
<td>Speed @ 48V after reduction (rad/sec)</td>
<td>7.92</td>
<td>5.24</td>
<td>6.13</td>
<td>6.13</td>
</tr>
</tbody>
</table>
DESIGN & DEVELOPMENT

Initial Design

Structural Analysis

Range of Motion

Aesthetic Aspect

Upper Link Protrudes Further in All Directions
PHYSICAL: FINAL ROBOT
WHOLE-BODY CONTROL FRAMEWORK

Encoder
Joint Position
Joint Velocity

IMU
Trunk Pitch Angle
Trunk Roll Angle

Robot Model
Kinematics
Dynamics

Contact-Consistent
Whole-body Control Framework
Commanding Torque

Joint Torque Controllers

Contact Information
Number of Contact
Contact State
Contact Position

Friction Model
Friction Compensation Torque

Joint Torque Controller

\[ \Gamma^k = \Gamma^k_{\text{task}} + \Gamma^k_{\text{null}} + \Gamma^k_{\text{gravity}} + \Gamma^k_{\text{friction}} \]

\[ \tau = H k_T i_m \]

\( H \): Gear Ratio
\( k_T \): Torque Constant (Nm/Amp)
\( i_m \): Input Current (Amp)

Step response of current (torque) controller
WHOLE-BODY CONTROL FRAMEWORK

Rigid Body Dynamics for Floating Base Robot considering contact constraint

\[ A(q)\ddot{q} + b(q, \dot{q}) + g(q) + J_c^T f_c = \Gamma \]

If contacts are stationary and rigid (\( \ddot{x}_c = 0, \dot{x}_c = 0 \))

\[ f_c = \bar{J}_c^T - \mu_c - p_c \]

Constrained Dynamics of Operational Space

\[ \Lambda(q)\ddot{x} + \mu(q, \dot{q}) + p(q) = F \]

\[ \Lambda(q) = (J A^{-1} N_c^T J_T)^{-1}, \quad \bar{J}_c^T = \Lambda J A^{-1} N_c^T \]

\[ \mu(q, \dot{q}) = \bar{J}_c b - \Lambda \dot{J} \ddot{q} + \Lambda J A^{-1} J_c^T \Lambda J_c \dot{q} \]

\[ p(q) = \bar{J}_c^T g(q), \quad N_c^T = I - J_c \bar{J}_c^T \]

Compose Control Torque only at Actuated Joints

\[ \Gamma^k = \bar{J}_c^T S^T F \]

\[ = \bar{J}_c^T S^T \Lambda (f^* + \mu + p) \]

Composed Control

\[ S = [0_{k \times 6} \quad I_{k \times k}] \]

\[ \bar{J}_c^T S^T \text{ (Inversion of } \bar{J}_c^T S^T \text{) is solved by minimizing joint acceleration energy.} \]

\[ f^* = k_p x_e + k_d \dot{x}_e \text{ for PD control.} \]
Gravity Compensation
BALANCING ALGORITHM

Estimate Contact Force/Moment

\[ F_c = P \tilde{J}_c^T (S^k)^T (\Gamma_{task}^k + \Gamma_{gravity}^k) \]

where,

\[ P = \begin{bmatrix} O_{Rr} & 0_{3 \times 3} & O_{Rl} & 0_{3 \times 3} \\ O_{Rr} & O_{\tilde{R}_r} & O_{Rr} & O_{\tilde{R}_l} \\ O_{Rl} & O_{\tilde{R}_l} & O_{Rl} & O_{Rl} \end{bmatrix} \]

COP Condition

If \(|M_x|/|F_z| < l_y/2\)

If \(|M_y|/|F_z| < l_x/2\)
in frame O

COP Control in Null Space

\[ \Gamma_{null}^k = (I - (J_{comZ}^k)^T (J_{comZ}^k)^T) \Gamma_0^k \]

\[ \Gamma_0^k = O_d \tilde{J}_c^T \begin{bmatrix} -O_{d M_x} \\ -O_{d M_y} \end{bmatrix} \]
BALANCING ALGORITHM

Double Support

External Force

COM Control Result

Projected COP Result
BALANCING ALGORITHM

Stepping Unknown Terrain

Upper Body Orientation Controlled for balancing
Orientation error about x-axis

COP Result
WHOLE-BODY CONTROL FRAMEWORK

Operational space control (PD Control)

$$\Gamma_{task}^k = (J^k)^T \Lambda (k_p x_e + k_d \dot{x}_e)$$

COM control result – Double Foot Contact

$$k_p = 100, k_d = 5$$
Low gain for compliant control
Friction Model

\[ \tau_f(\dot{q}_j) = \text{sign}(\dot{q}_j)(\tau_c + (\tau_s - \tau_c)e^{-(\dot{q}_j/\alpha)\delta}) \]

\[ \dot{q}_{j,estimated} = \ddot{q}_{j,estimated}\Delta t \]

\[ \ddot{q}_{j,estimated} = A^{-1}(I - J^T_c J^T_c)(S^k)^T(\Gamma^k_{task} + \Gamma^k_{null}) \]

Joint space control results

Operational space control results
Distribute Contact Force/Moment w/o motion control

6~11(sec)
Increase $F_c$ of right foot $F_{c,init}$ to $1.5F_{c,init}$ during 5 (sec).

19~24(sec)
Decrease $F_c$ of right foot $1.5F_{c,init}$ to $F_{c,init}$ during 5 (sec).

Contact Force/Moment Generation Result

COM Motion during Contact Force/Moment generation
**UNEXPECTED CONTACT ON GROUND**

- Humanoid robot always has contact between foot and ground.
- **Perception error** of the ground and **unexpected contact** can cause serious **balance problem** of humanoid robot.
- Robot cannot avoid every unexpected contacts.

## Contact Estimation Algorithm Overview

<table>
<thead>
<tr>
<th>Compliant Motion Control</th>
<th>Contact Recognition</th>
<th>Operate Active Sensing Algorithm</th>
<th>Estimate Contact Ground Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact occurs</td>
<td>Control Error &gt; Threshold</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Walking & Balancing algorithm**

- Slope & Height of Ground
- Allowable ZMP(CoP) Area
CONTACT ESTIMATION WITH FOOT

Move Center of Pressure (CoP) to generate rotation motion

\[ \Gamma = (J_1^k)^T F + (N^k)^T (J_2^k)^T \left( \Lambda_2 (k_p x_e + k_d \dot{x_e}) \right) + G \]

1st priority
- Foot Force Z
- Foot Moment (Y)

2nd priority
- Upper body Position/Orientation
- Foot Position(X,Y)/Orientation(X,Z)
UNEXPECTED CONTACT ON GROUND

Robot for Experiments

DYROS Humanoid Leg

• 12-DOF Torque Control Robot with Electric Motor
• Whole-body controller considering full-body dynamics
• Height : 1.425 (m), Weight : 54.6 (kg)

Terrain used for experiments
UNEXPECTED CONTACT ON GROUND

Estimated Slope: 0.187 (rad)

Cinder Block Slope: 0.261 (rad)
UNEXPECTED CONTACT ON GROUND

Estimated Contact Edge \( x=0.2052 \text{ (m)} \) \( z=0.0665 \text{ (m)} \)

Actual Contact Edge \( x=0.2200 \text{ (m)} \) \( z=0.0600 \text{ (m)} \)
PEG-IN-HOLE WITH TWO HANDS

Robotic hand
• 4 fingers
• 4 joints each finger
• Torque input

Dual arm
• 8 joints each arm
• Torque input

Torso
• 2 joints
• Torque input

The Robot is developed by the team of Dr. Ji-Hun Bae at KITECH (Korea Institute of Industrial Technology)
TWO ARMS WITH TWO HANDS

- The peg and hole are lying on the table
- Location information of the objects is recognized by Kinect sensor
- Mass of the objects
  - Hole: 310 g
  - Peg: 90 g
- Diameter of the objects
  - Hole: 50.0 mm
  - Peg: 49.9 mm
MEASURED HOLE AND PEG POSITION

Recognize Iterative closest point

<table>
<thead>
<tr>
<th></th>
<th>Hole</th>
<th>Peg</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Trials</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Average</td>
<td>[0.706 -0.148 -0.114]</td>
<td>[0.712 0.152 -0.112]</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>1.3 mm</td>
<td>0.91 mm</td>
</tr>
</tbody>
</table>
PEG-IN-HOLE STRATEGY

Using “Intuitive peg-in-hole strategy”
• Generating the force toward the hole
• Searching the hole by rubbing motion
• Wiggling the peg to fit the orientation
• Screwing the peg to overcome friction
PEG-IN-HOLE EXPERIMENT
SUMMARY

Balancing  Active Sensing for Terrain

Peg-in-hole Strategy
THANK YOU!

QUESTIONS?