BALANCING AND ACTIVE SENSING USING WHOLE-BODY CONTROL FRAMEWORK

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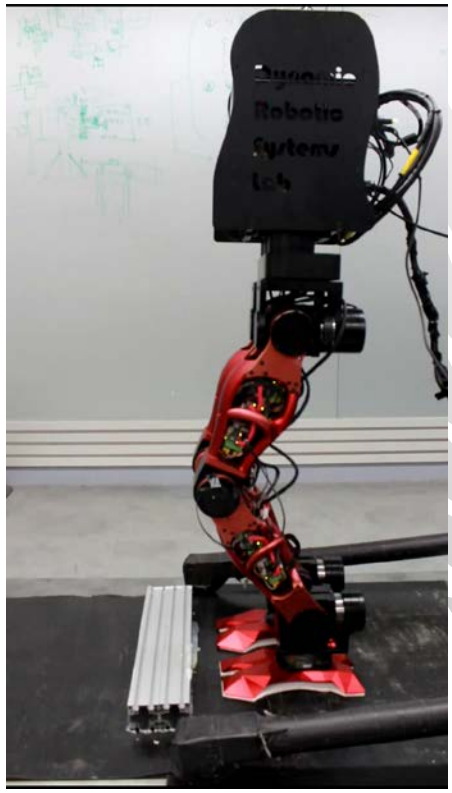
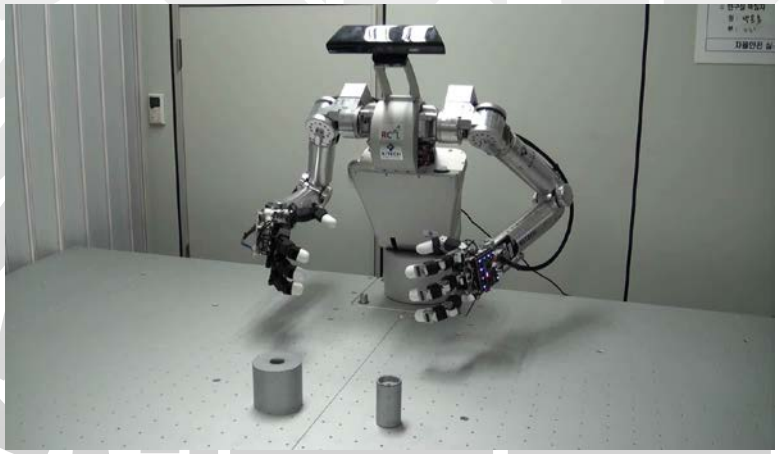
BALANCING AND ACTIVE SENSING

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

Balancing



Active Sensing for Terrain



Peg-in-hole Strategy

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

Joint	Peak torque (Nm)	Peak velocity (rad/sec)	RMS torque (Nm)	RMS velocity (rad/sec)
1	0	0	0	0
2	0	0	0	0
3	27.030	2.594	11.205	0.832
4	182.816	4.916	85.094	2.491
5	24.027	3.286	10.053	1.135
6	0	0	0	0

Walking Simulation

Joint	Peak torque (Nm)	Peak velocity (rad/sec)	RMS torque (Nm)	RMS velocity (rad/sec)
1	53.944	0.811	16.869	0.187
2	91.258	0.497	46.224	0.252
3	178.823	2.536	68.671	1.124
4	86.952	2.145	48.540	0.873
5	114.165	2.043	30.220	0.780
6	24.255	0.628	6.562	0.231

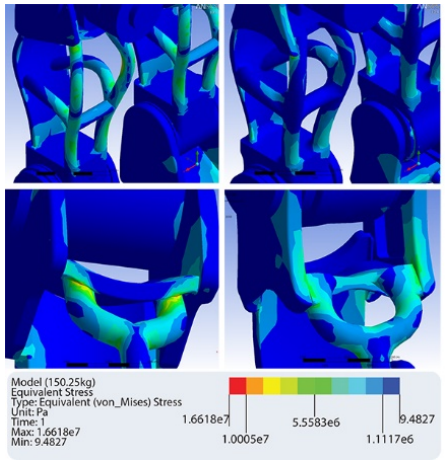
PROCESS: SIMULATION

- Motor Torques

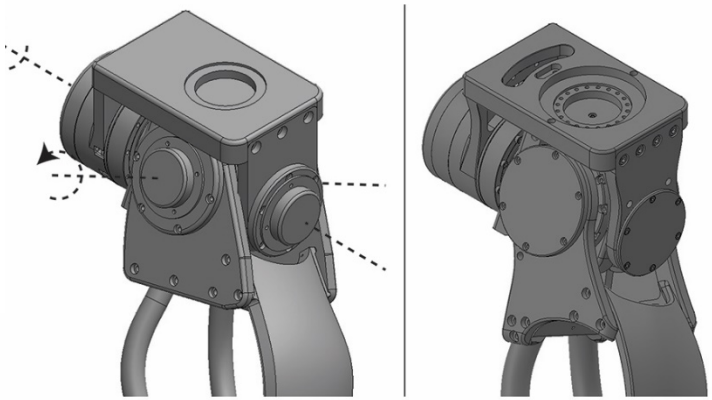
Joint	Hip Yaw	Hip Roll	Hip Pitch	Knee Pitch	Ankle Pitch	Ankle Roll
Joint Number	1, 7	2, 8	3, 9	4, 10	5, 11	6, 12
Motor Name	KOLLMORGEN RBE(H) 01811 C	KOLLMORGEN RBE(H) 01812 C	KOLLMORGEN RBE(H) 01813 C	KOLLMORGEN RBE(H) 01813 C	KOLLMORGEN RBE(H) 01813 C	KOLLMORGEN RBE(H) 01810 C
Max Cont. Output Power (W)	300	364	427	427	427	209
Cont. Torque (N·m)	0.856	1.220	1.54	1.54	1.54	0.429
Peak Torque (N·m)	3.04	4.62	6.15	6.15	6.15	1.53
Speed @ 48V (RPM)	3780	2500	2927	2927	2927	7511
Harmonic Drive Name	SHD-17-50-2SH	SHG-20-50-2SO	SHG-20-50-2SO	SHG-20-50-2SO	SHG-20-50-2SO	SHG-17-50-2SO
Reduction Ratio	50	50	50	50	50	50
Cont. Torque after reduction (N·m)	42.8	61.0	77.0	77.0	77.0	21.45
Peak Torque after reduction (N·m)	152.0	231.0	307.5	307.5	307.5	76.5
Speed @ 48V after reduction (rad/sec)	7.92	5.24	6.13	6.13	6.13	15.73

DESIGN & DEVELOPMENT

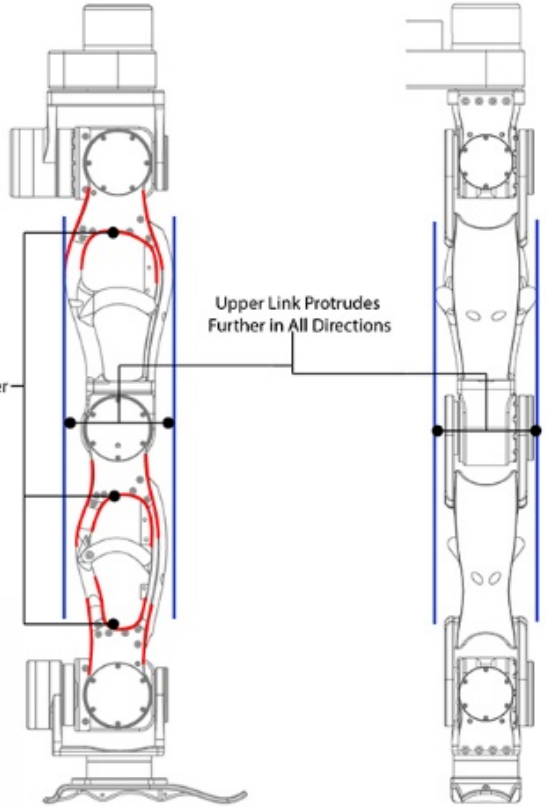
Initial Design



Structural Analysis

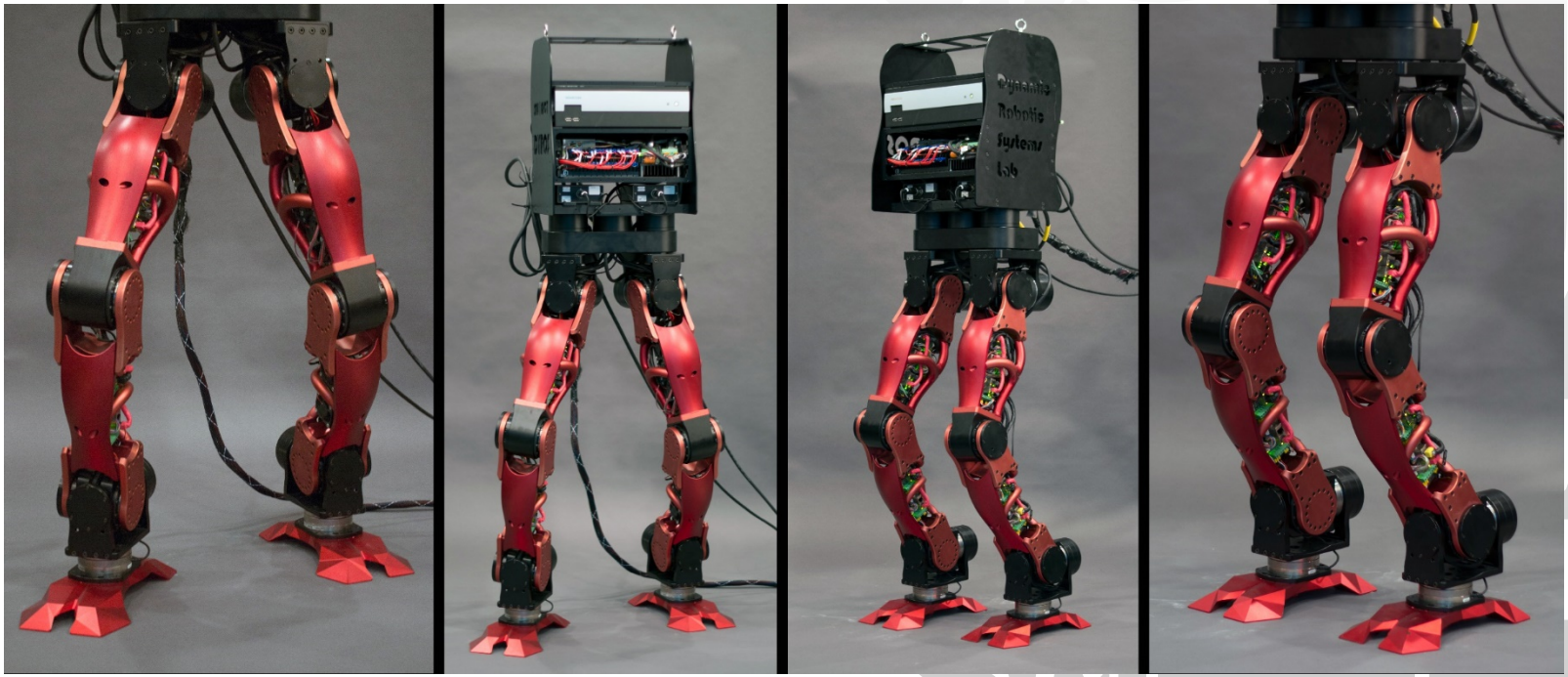


Range of Motion

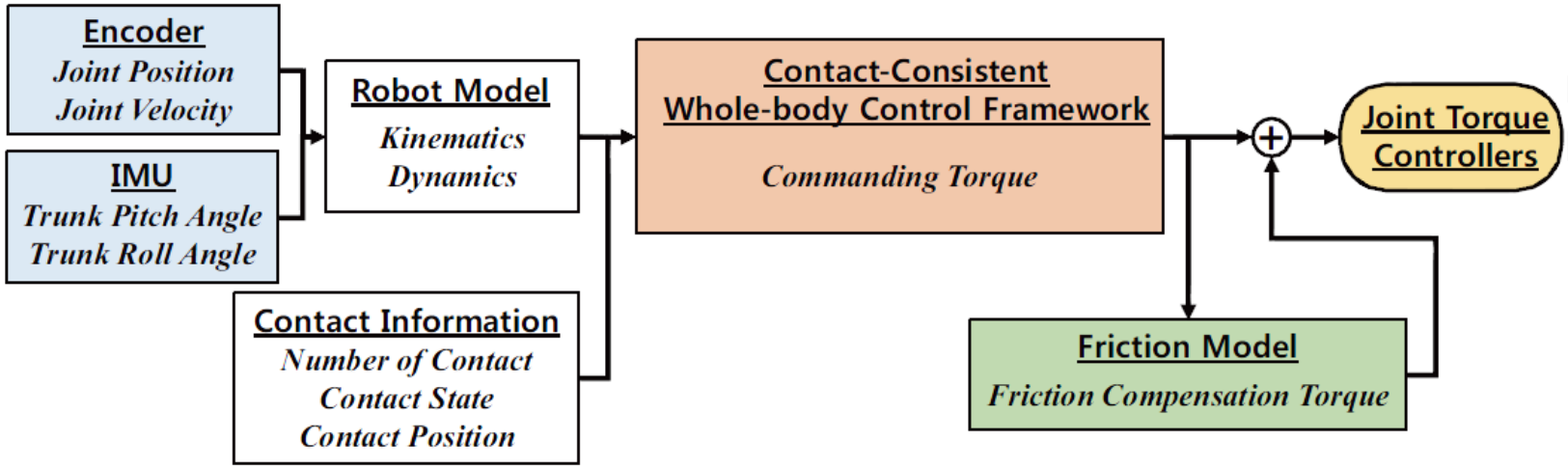


Aesthetic Aspect

PHYSICAL: FINAL ROBOT



WHOLE-BODY CONTROL FRAMEWORK



$$\Gamma^k = \Gamma^k_{task} + \Gamma^k_{null} + \Gamma^k_{gravity} + \Gamma^k_{friction}$$

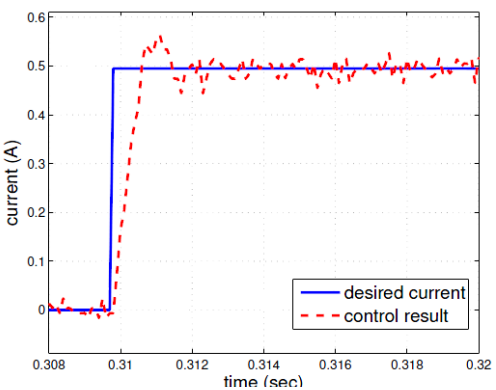
Joint Torque Controller

$$\tau = H k_T i_m$$

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

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

$$\Lambda(q) = (JA^{-1}N_c^T J^T)^{-1}, \qquad \bar{J}^T = \Lambda J A^{-1} N_c^T$$

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

$$p(q) = \bar{J}^T g(q), \qquad N_c^T = I - J_c^T \bar{J}_c^T$$

Compose Control Torque only at Actuated Joints

$$\Gamma^k = \overline{\bar{J}^T S^T} F$$
$$= \overline{\bar{J}^T S^T} \Lambda (f^* + \mu + p)$$

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

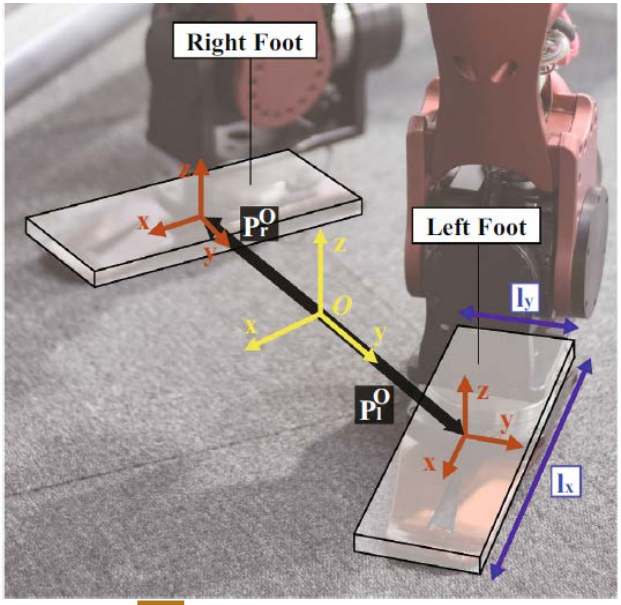
$\overline{\bar{J}^T S^T}$(Inversion of $\bar{J}^T S^T$) is solved by minimizing joint acceleration energy.

$f^* = k_p x_e + k_d \dot{x}_e$ for PD control.

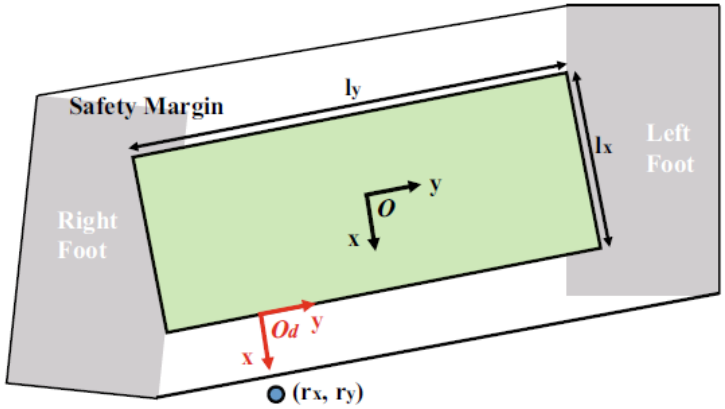
WHOLE-BODY CONTROL FRAMEWORK

Gravity Compensation

BALANCING ALGORITHM



Project to
Single Contact Plane



Estimate Contact Force/Moment

$$F_c = P\bar{J}_c^T (S^k)^T (\Gamma_{task}^k + \Gamma_{gravity}^k)$$

where,

$$P = \begin{bmatrix} {}^O R_r & 0_{3\times3} & {}^O R_l & 0_{3\times3} \\ {}^O R_r \, {}^O\widehat{P}_r & {}^O R_r & {}^O R_l \, {}^O\widehat{P}_l & {}^O R_l \end{bmatrix}$$

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

$$\Gamma_{null}^k = (I - (J_{comZ}^k)^T \overline{(J_{comZ}^k)^T})\, \Gamma_0^k$$

$$\Gamma_0^k = {}^{O_d}\bar{J}_c^T \begin{bmatrix} -{}^{O_d}M_x \\ -{}^{O_d}M_y \end{bmatrix}$$

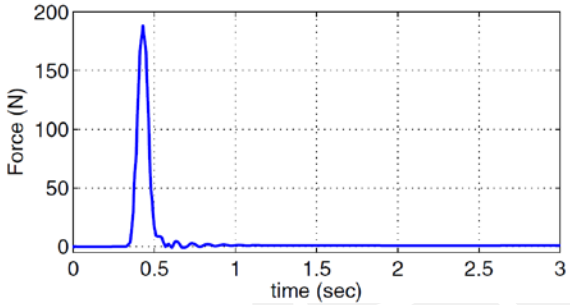
→ Torque for Balancing

Yisoo Lee, Soonwook Hwang, Jaeheung Park, BALANCING OF HUMANOID ROBOT USING CONTACT FORCE/MOMENT CONTROL BY TASK-ORIENTED WHOLE-BODY CONTROL FRAMEWORK, Autonomous Robots, Online Published

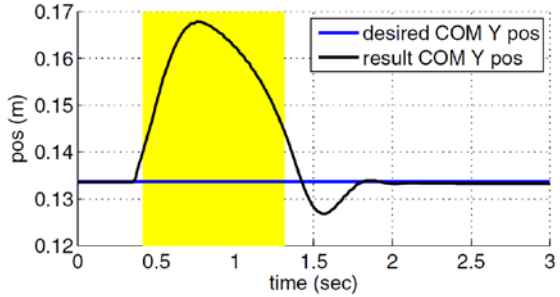
BALANCING ALGORITHM

Double Support

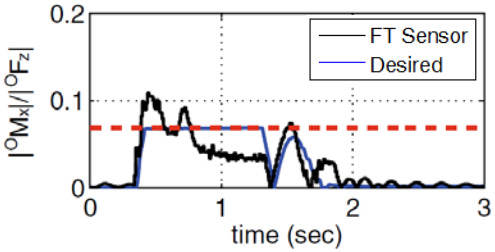
External Force

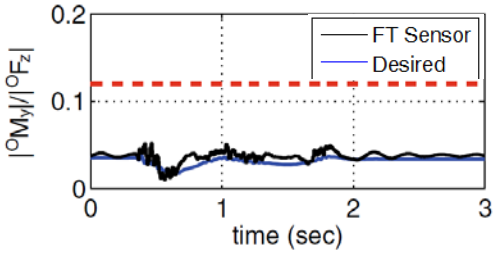


COM Control Result



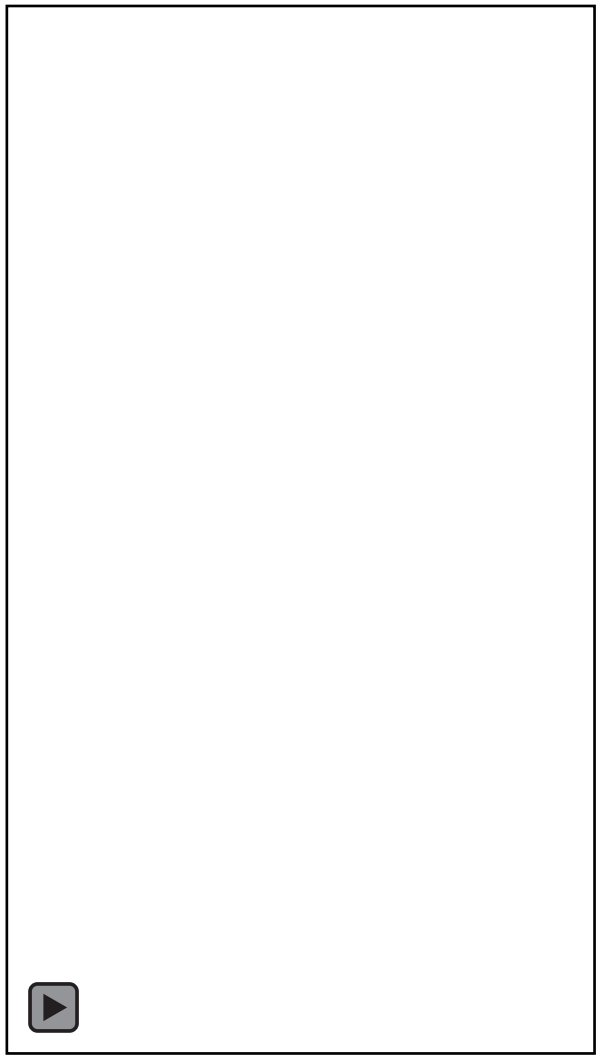
Projected COP Result



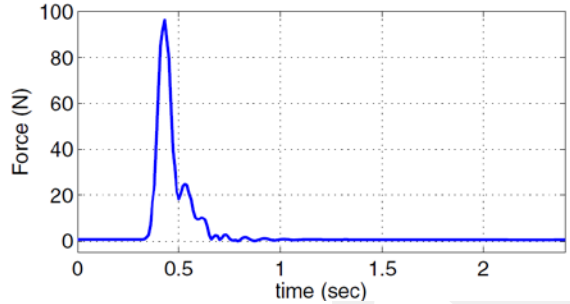


BALANCING ALGORITHM

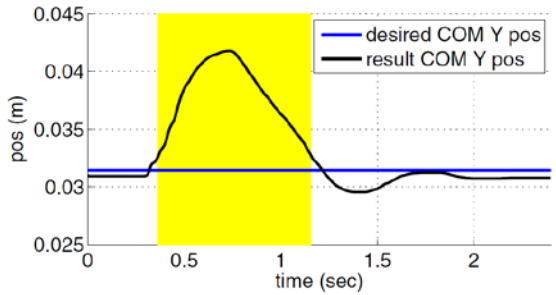
Single Support



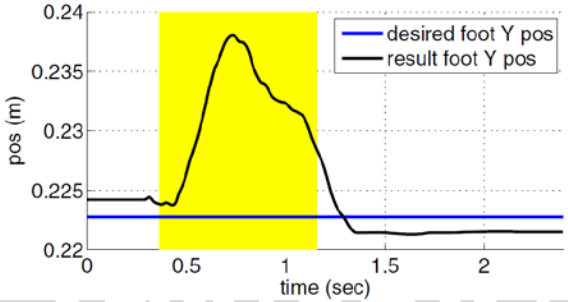
External Force



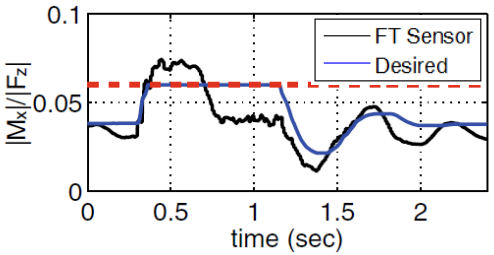
COM Control Result

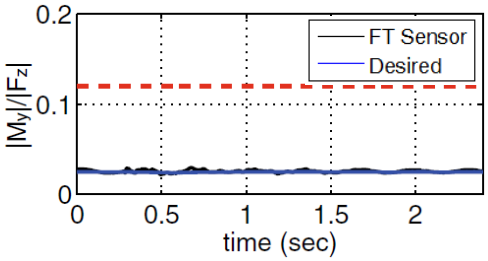


Foot Control Result



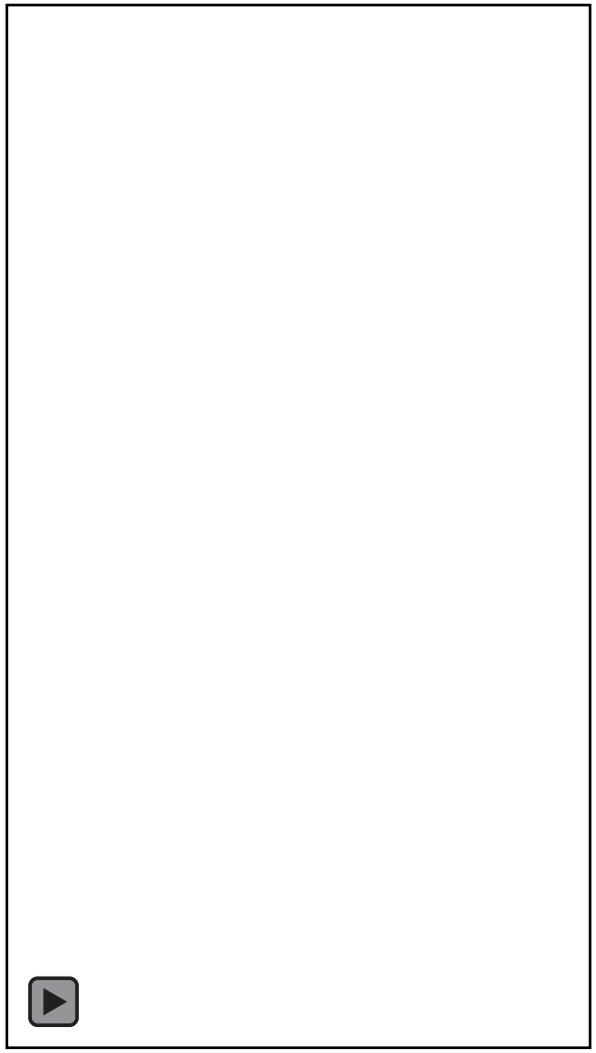
COP Result





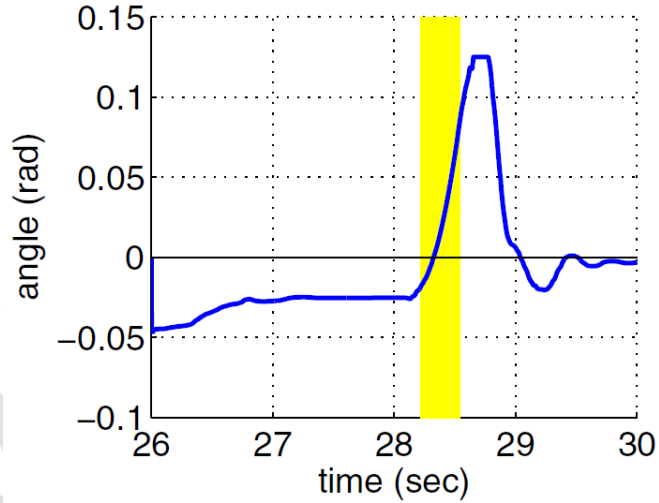
BALANCING ALGORITHM

Stepping Unknown Terrain

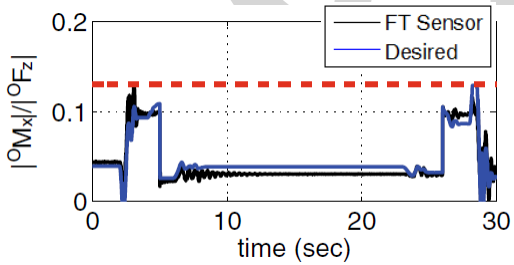


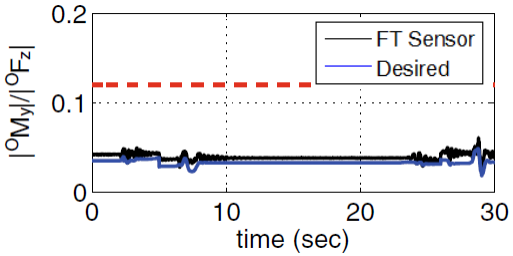
Upper Body Orientation Controlled for balancing

Orientation error about x-axis



COP Result





WHOLE-BODY CONTROL FRAMEWORK

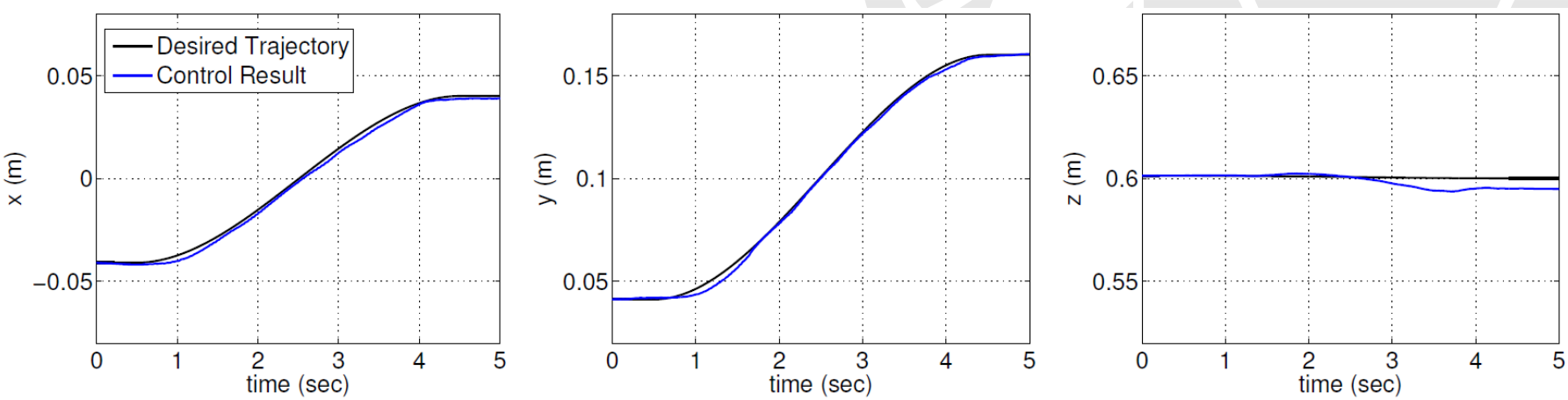
Operational space control (PD Control)

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

COM control result – Double Foot Contact

$k_p = 100, k_d = 5$

Low gain for compliant control



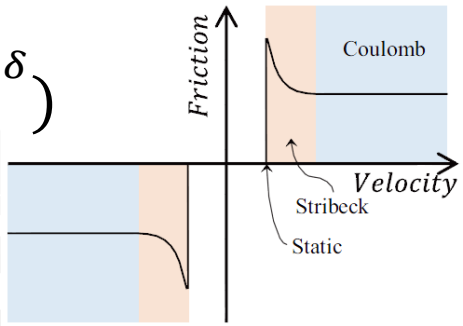
JOINT FRICTION COMPENSATION

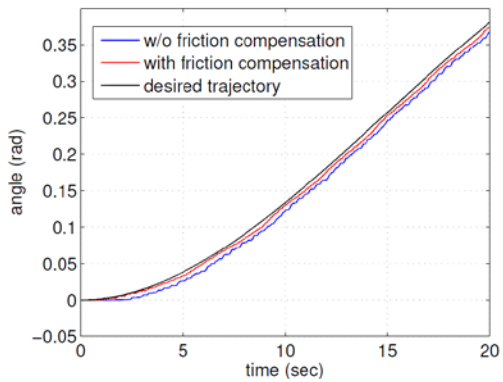
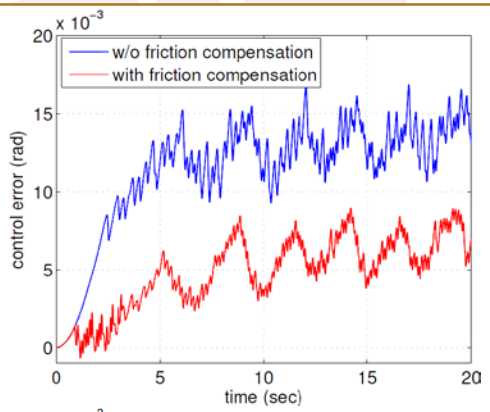
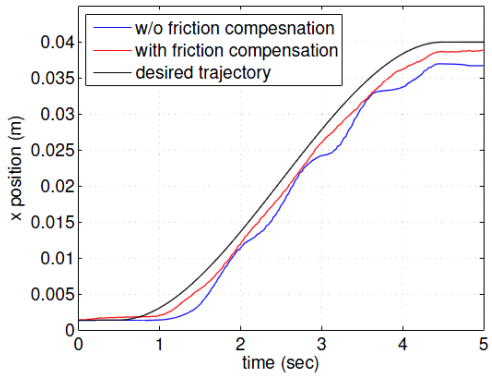
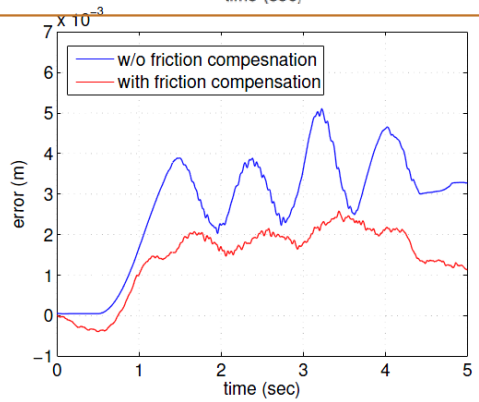
Friction Model

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

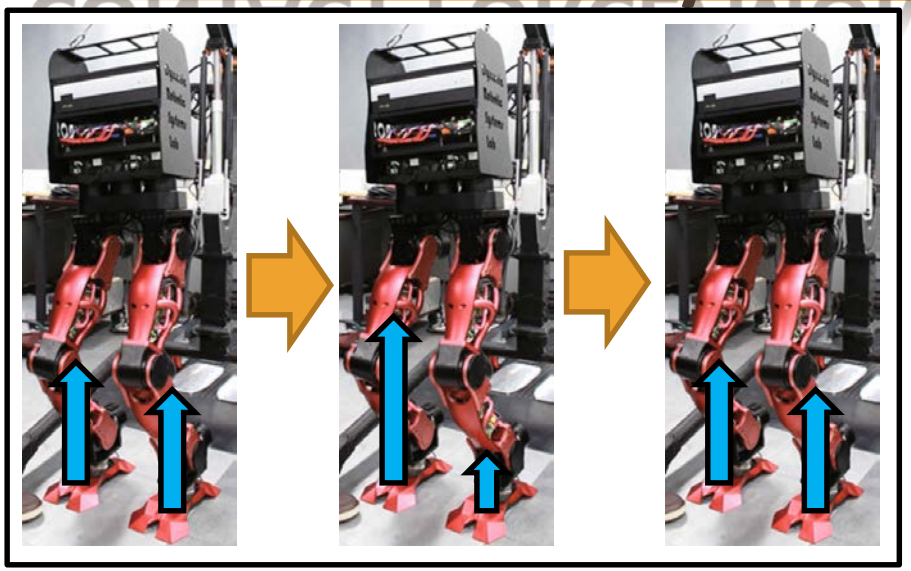
$$\dot{q}_{j,estimated} = \ddot{q}_{j,estimated}\Delta t$$

$$\ddot{q}_{j,estimated} = A^{-1}(I - J_c^T \bar{J}_c^T)(S^k)^T(\Gamma_{task}^k + \Gamma_{null}^k)$$



Joint space control results		
Operational space control results		

CONTACT FORCE/MOMENT DISTRIBUTION



Distribute Contact Force/Moment w/o motion control

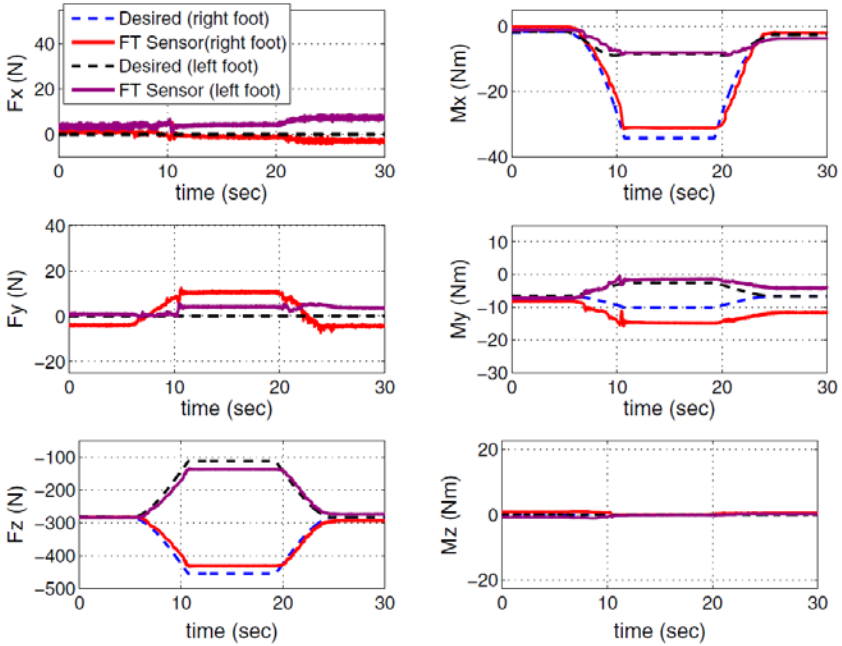
6~11(sec)

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

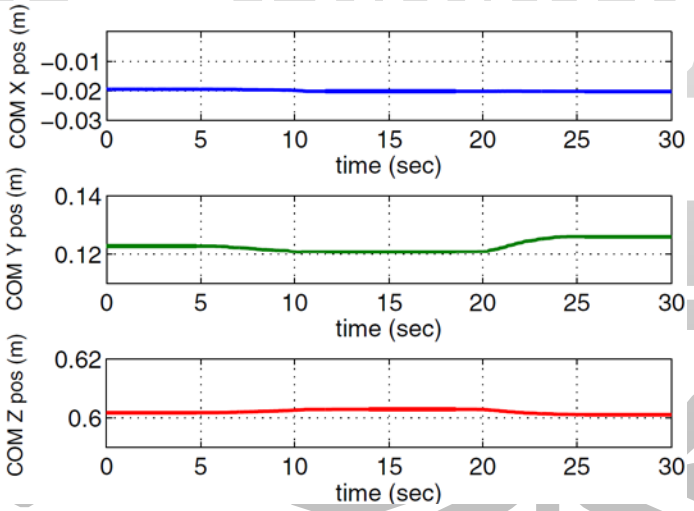
19~24(sec)

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

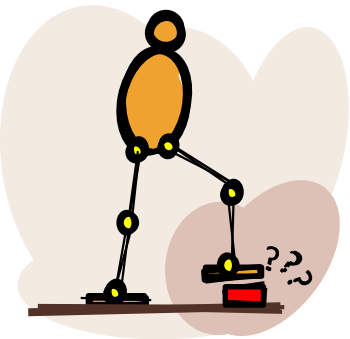
Contact Force/Moment Generation Result



COM Motion during Contact Force/Moment generation

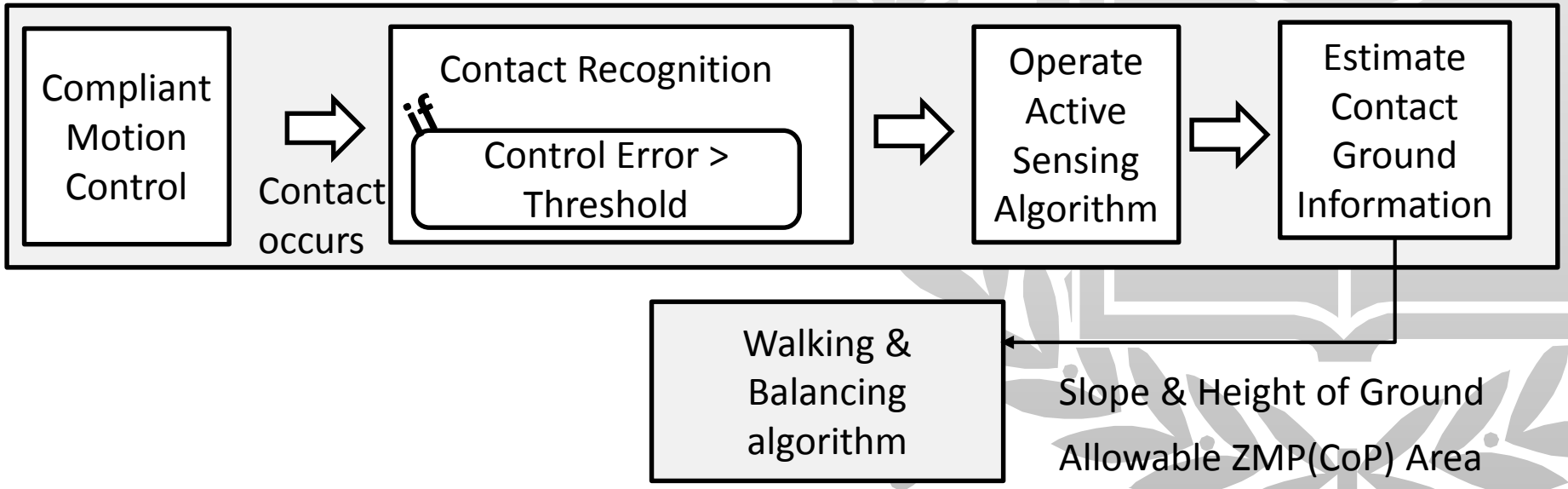


UNEXPECTED CONTACT ON GROUND

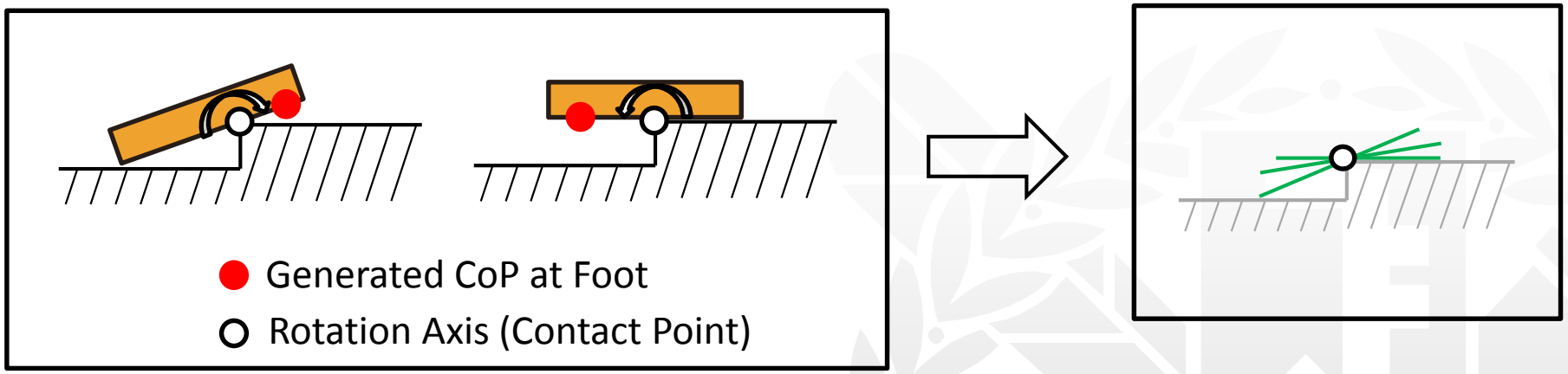


- Humanoid robot always has contact between foot and ground.
- **Perception error** of the ground and **unexpected contact** can cause serious balance problem of humanoid robot.
- Robot cannot avoid every unexpected contacts.

Contact Estimation Algorithm Overview



CONTACT ESTIMATION WITH FOOT



Move Center of Pressure(CoP) to generate rotation motion

$$\Gamma = \underbrace{\left(J_1^k\right)^T F}_{1^{st}\text{ priority}} + \left(N^k\right)^T \left(J_2^k\right)^T \underbrace{\left(\Lambda_2\left(k_p x_e + k_d \dot{x}_e\right)\right)}_{2^{nd}\text{ priority}} + G$$

1st priority

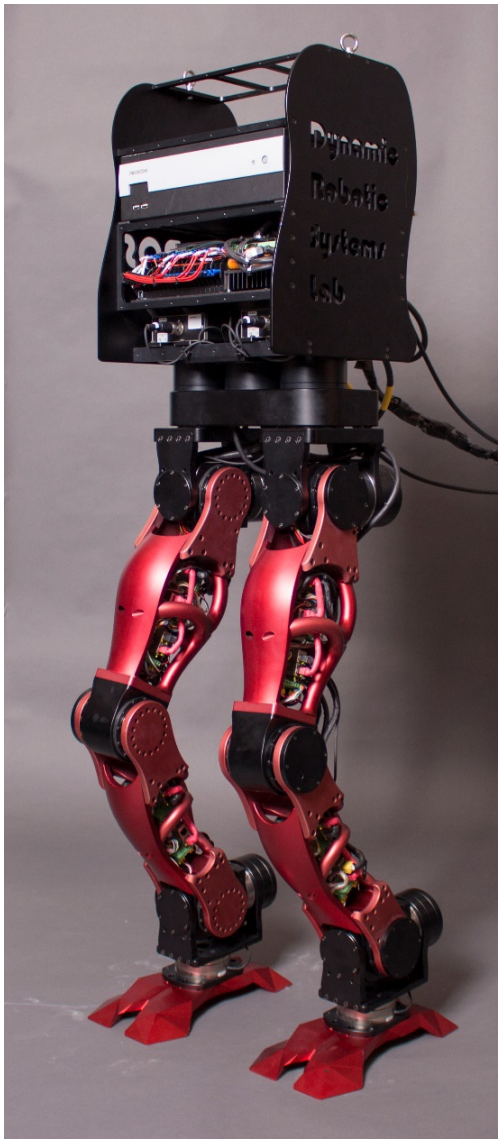
[Foot Force Z
Foot Moment (Y)]

2nd priority

[Upper body Position/Orientation
Foot Position(X,Y)/Orientation(X,Z)]

UNEXPECTED CONTACT ON GROUND

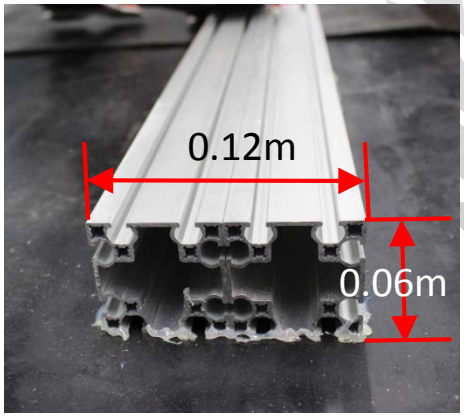
Robot for Experiments

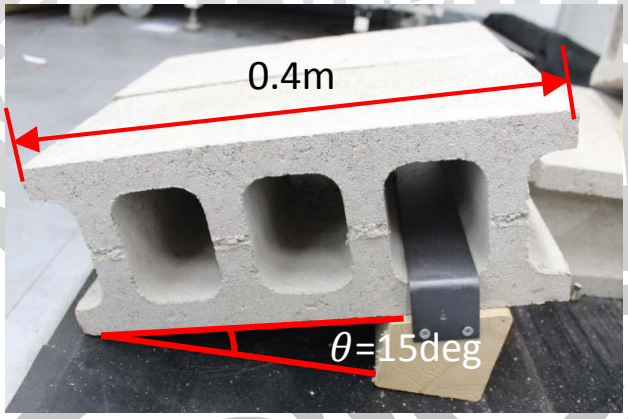


DYROS Humanoid Leg

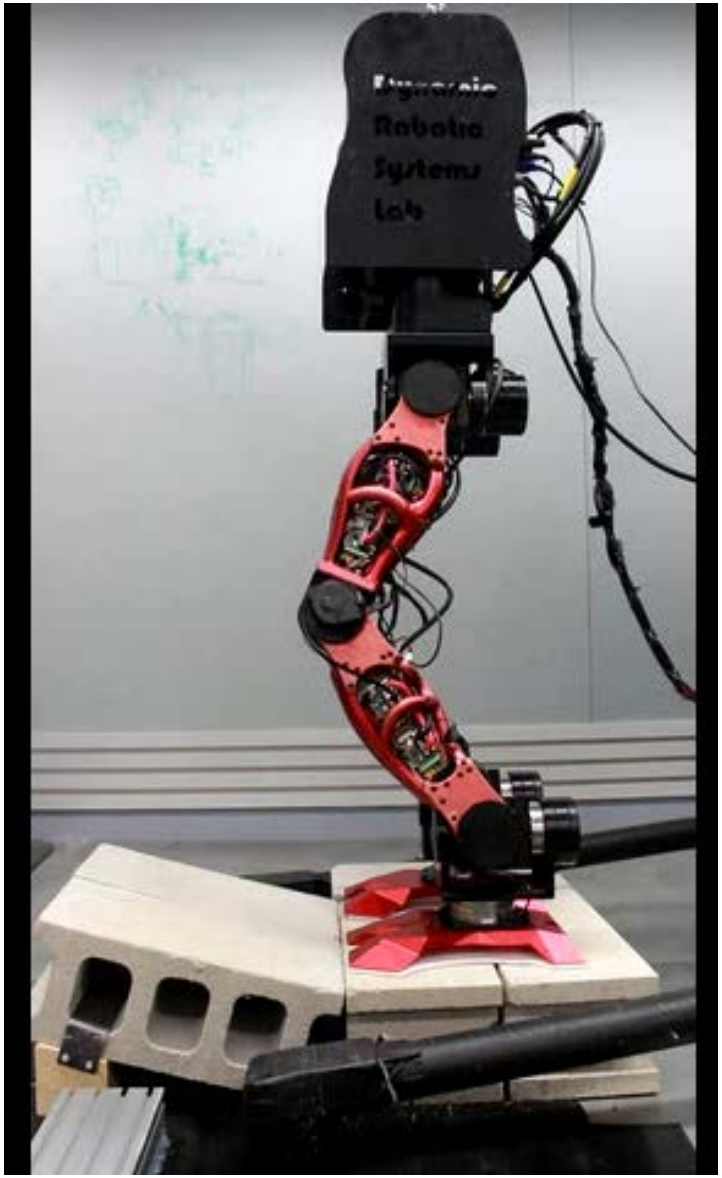
- 12-DOF Torque Control Robot with Electric Motor
- Whole-body controller considering full-body dynamics
- Height : 1.425 (m), Weight : 54.6 (kg)

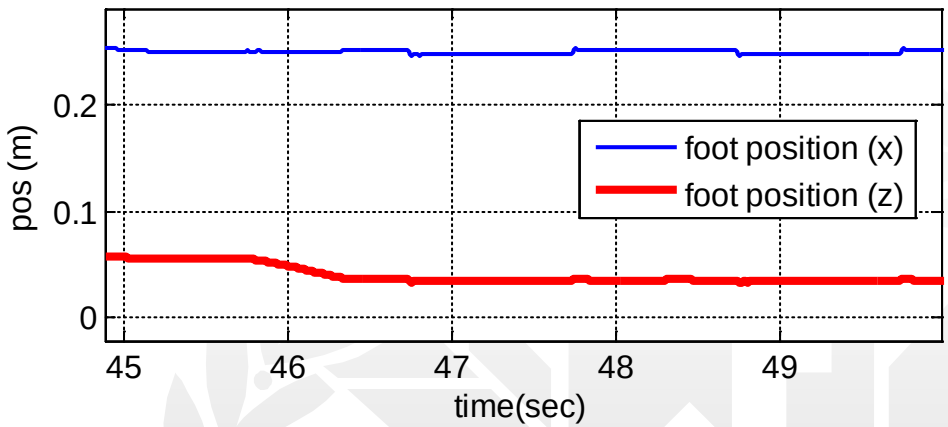
Terrain used for experiments

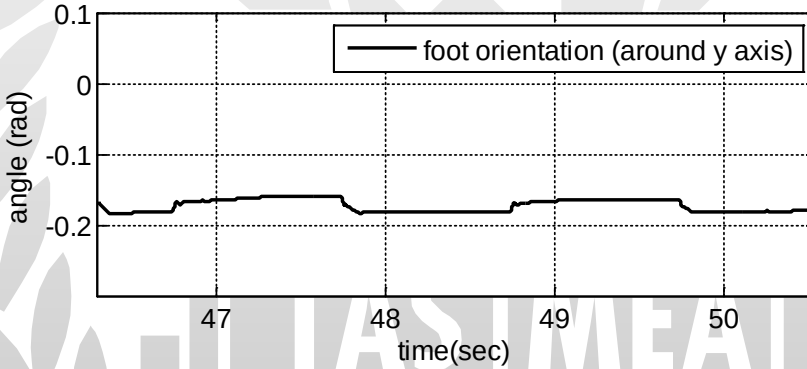




UNEXPECTED CONTACT ON GROUND



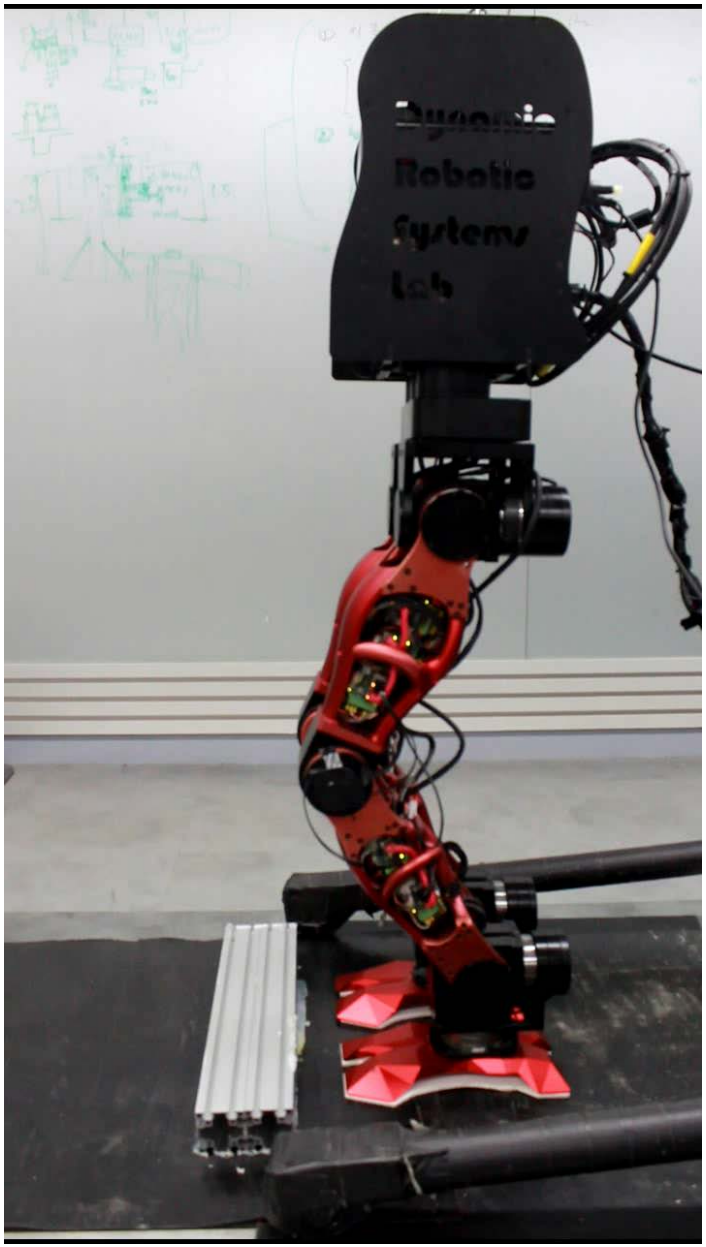


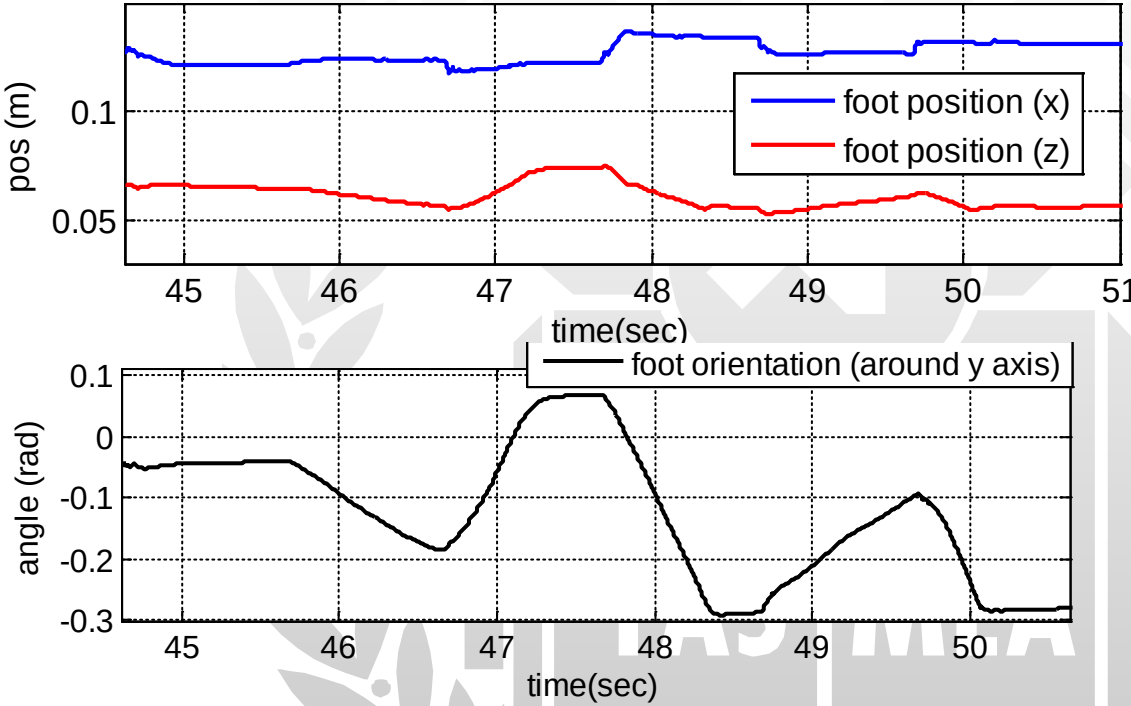


Estimated Slope : 0.187 (rad)

Cinder Block Slope : 0.261 (rad)

UNEXPECTED CONTACT ON GROUND





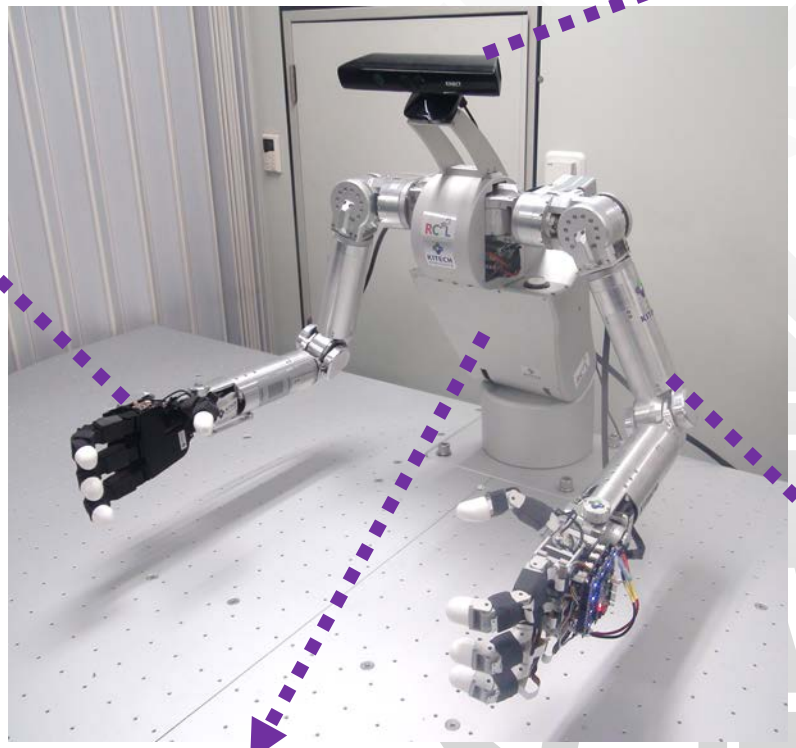
Estimated Contact Edge x=0.2052 (m) z=0.0665 (m)

Actual Contact Edge x=0.2200 (m) z=0.0600 (m)

PEG-IN-HOLE WITH TWO HANDS

Kinect 1.0

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



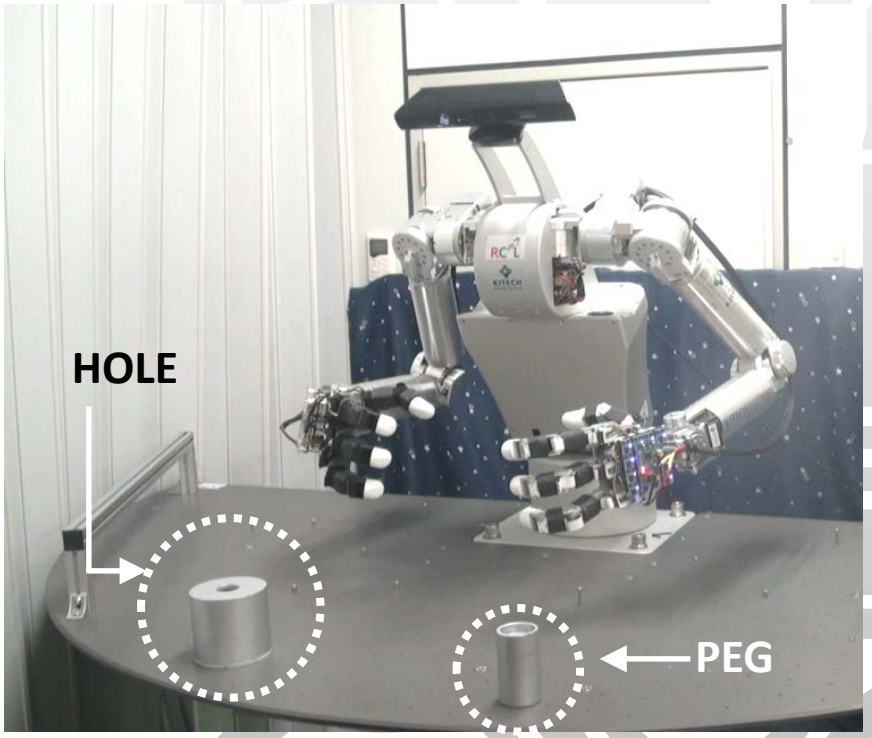
Dual arm
- 8 joints each arm
- Torque input

Torso
- 2 joints
- Torque input

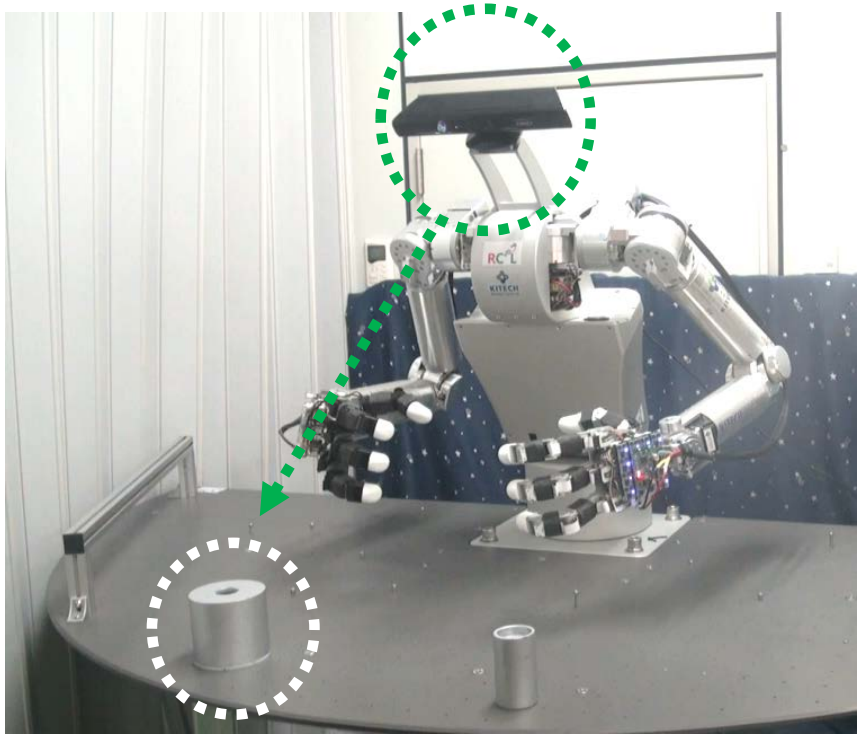
- **The Robot is developed by the team of Dr. Ji-Hun Bae at KITECH (Korea Institute of Industrial Technology)**

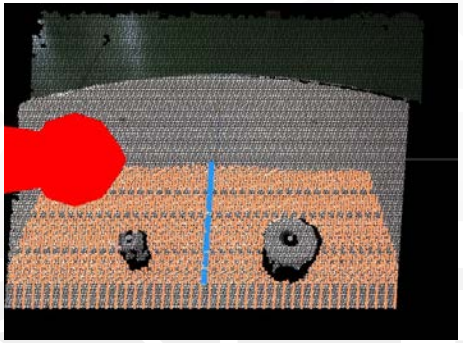
TWO ARMS WITH TWO HANDS

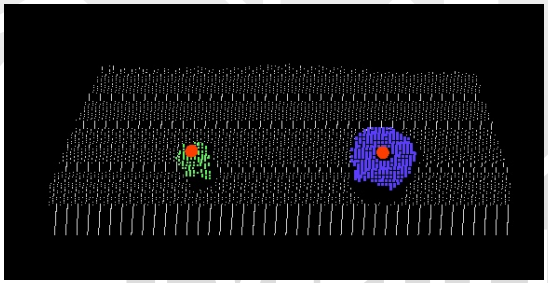
- The peg and hole are lying on the table
- Location information of the objects is recognized by Kinect sensor
- Mass of the objects
  - Hole : 310 g
  - Peg : 90 g
- Diameter of the objects
  - Hole : 50.0 mm
  - Peg : 49.9 mm



MEASURED HOLE AND PEG POSITION







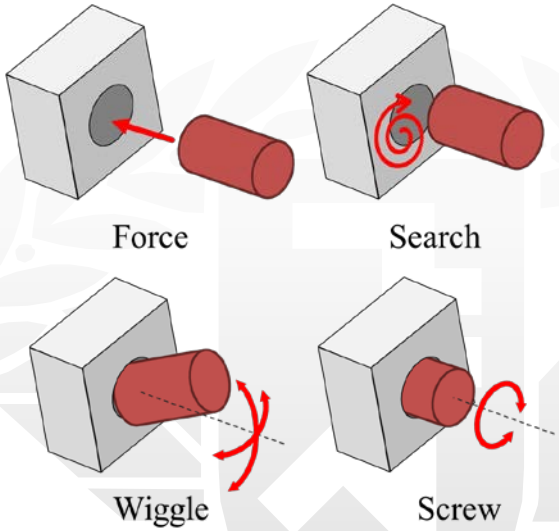
Iterative closest point

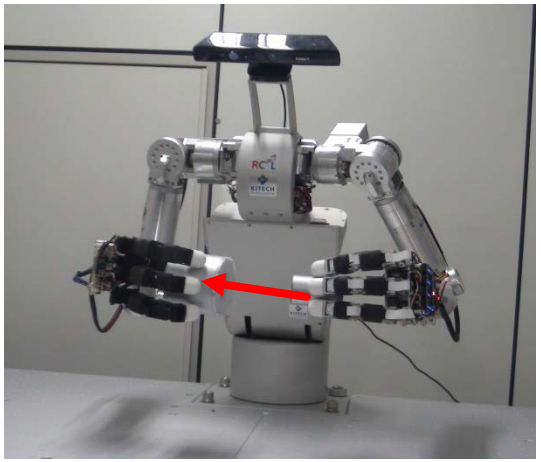
	Hole	Peg
# of Trials	300	300
Average	[0.706 -0.148 -0.114]	[0.712 0.152 -0.112]
Standard Deviation	1.3 mm	0.91 mm

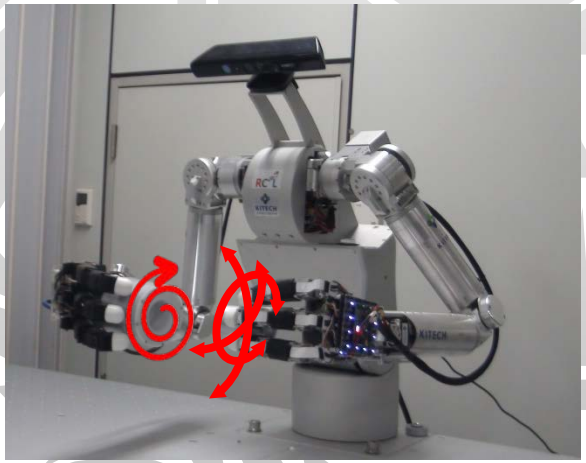
PEG-IN-HOLE STRATEGY

Using “Intuitive peg-in-hole strategy”

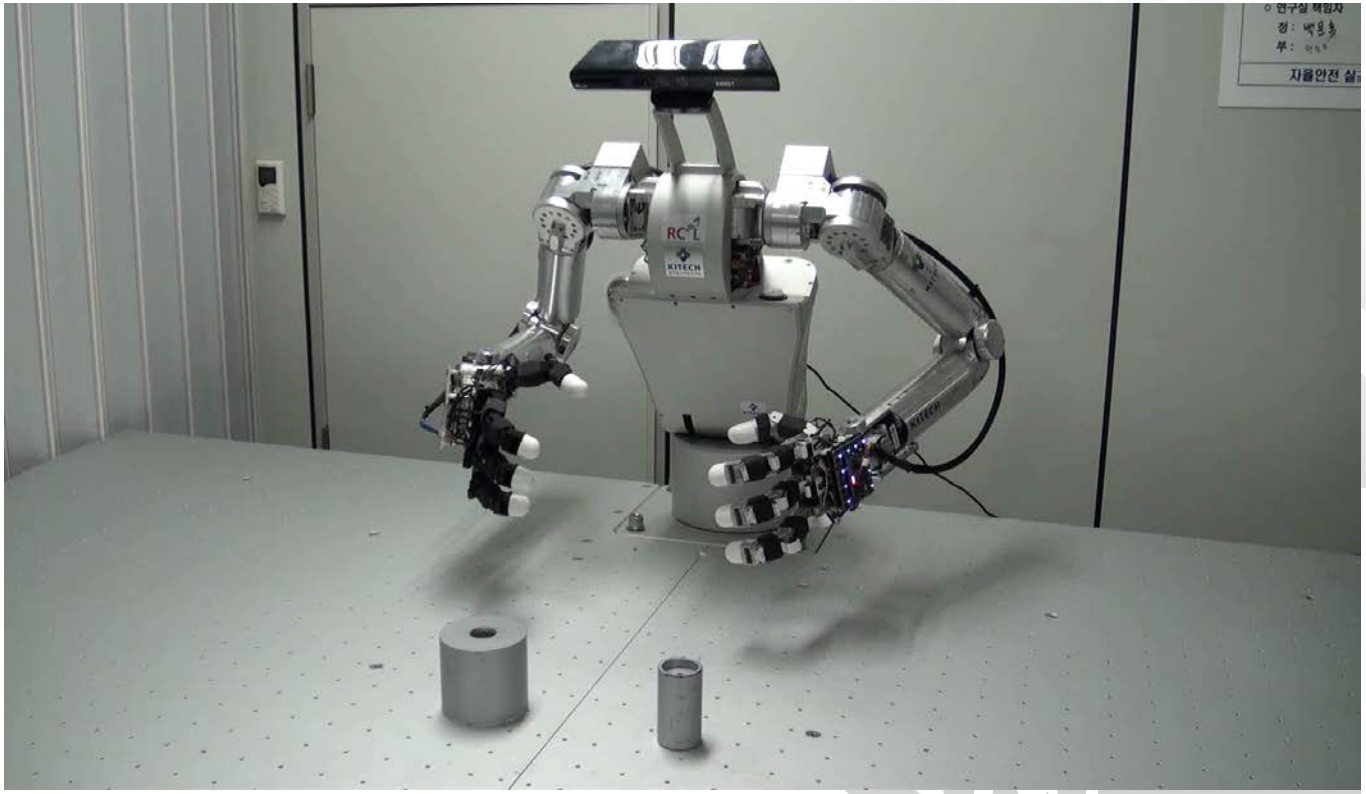
- Generating the force toward the hole
- Searching the hole by rubbing motion
- Wiggling the peg to fit the orientation
- Screwing the peg to overcome friction





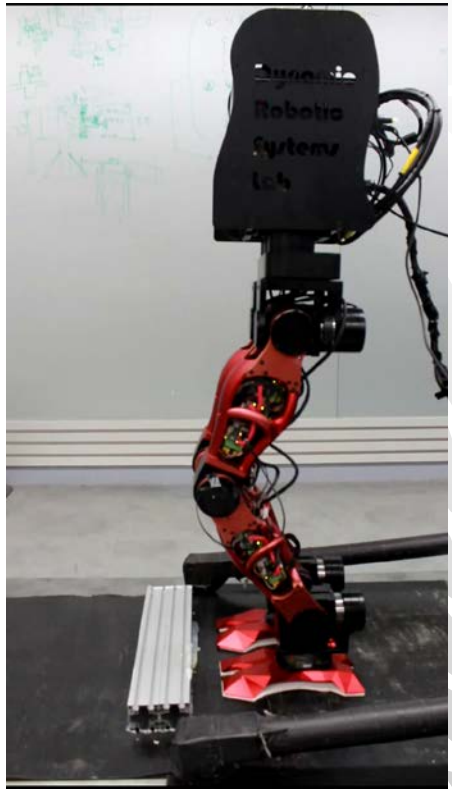


PEG-IN-HOLE EXPERIMENT

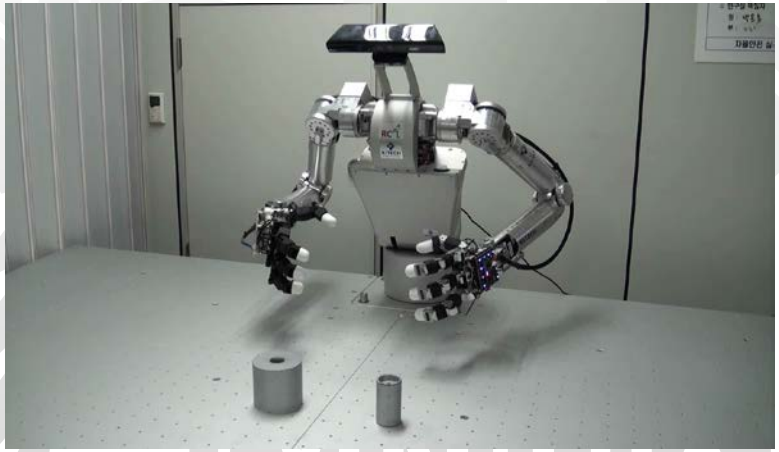


SUMMARY

Balancing



Active Sensing for Terrain



Peg-in-hole Strategy

THANK YOU!

QUESTIONS?