WS: New Bodies for Cognitive Humanoids
IEEE Humanoids2011
Bled, Slovenia, 2011.10.26

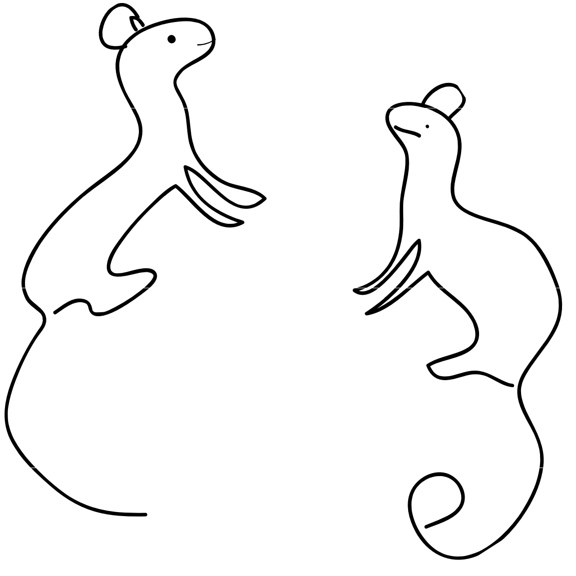
On the Requirements of New Actuators for the New Body of Humanoids

Yoshihiko Nakamura and Hiroshi Kaminaga
The University of Tokyo

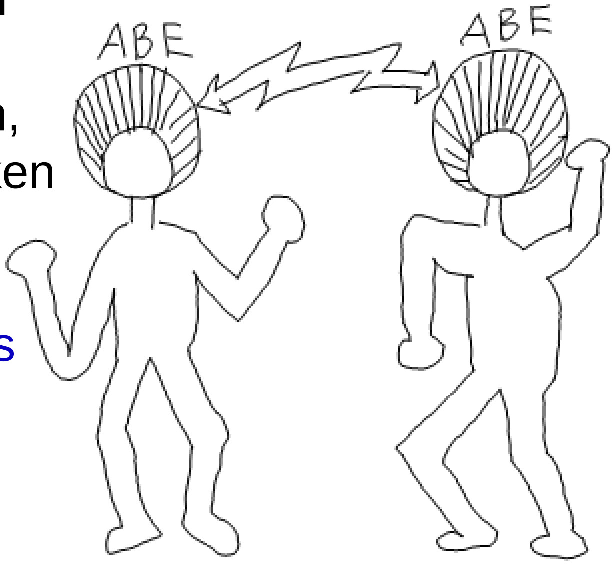
We would like to acknowledge the great contributions of students who wrote their dissertations at our laboratory, in the Department of Mechano-Informatics, University of Tokyo, and were the coauthors of each of papers from which we picked out the material of this talk.

Yoshihiko Nakamura and Hiroshi Kaminaga

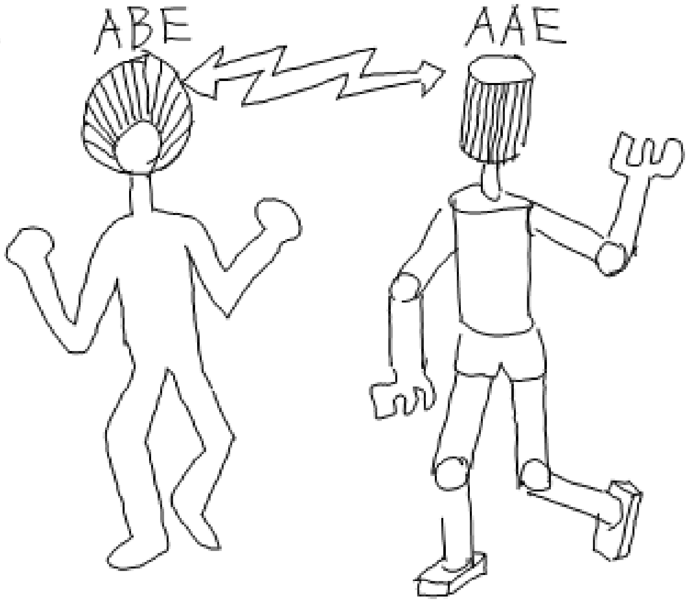
Understanding → Prediction and Action (for survival)



understand human behavior, body sensation, intention, and interpret by spoken language using anthropomorphic biological equipments (ABE)



understand human behavior, body sensation, intention, and interpret by spoken language using anthropomorphic biological equipments (ABE)



understand humanoid behavior, intention, and interpret by spoken language using anthropomorphic biological equipments (ABE)

understand human behavior, body sensation, intention, and interpret by spoken language using anthropomorphic artificial equipments (AAE)

generate robot behaviors so that its intention is understood by ABE.

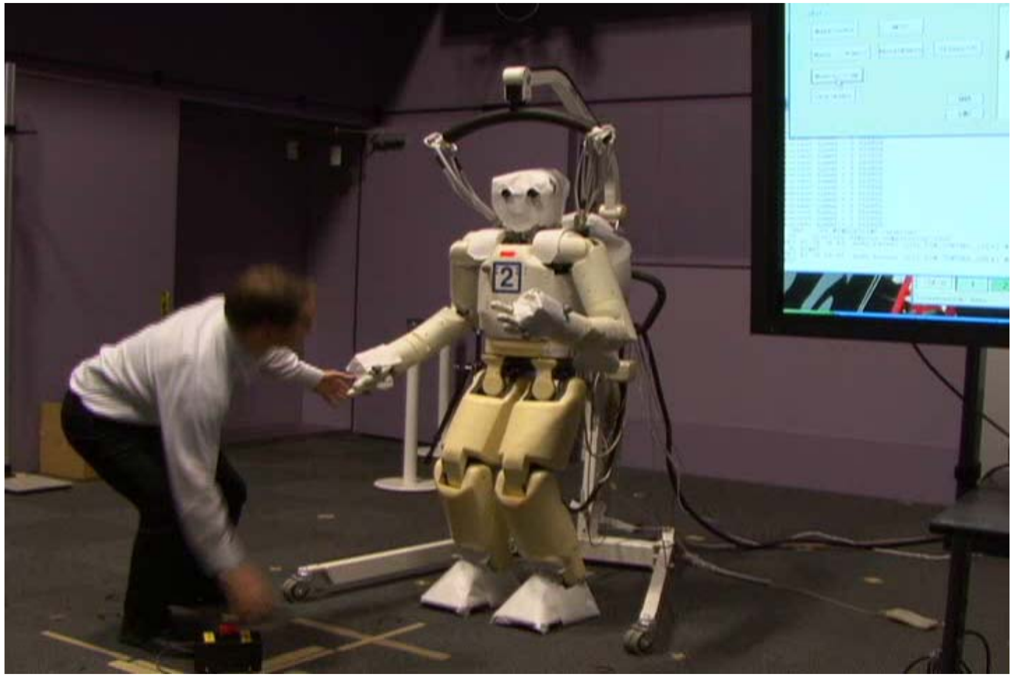
IROS 2009

Base Force/Torque Sensing for Position based Cartesian Impedance Control

Christian Ott*
Yoshihiko Nakamura**

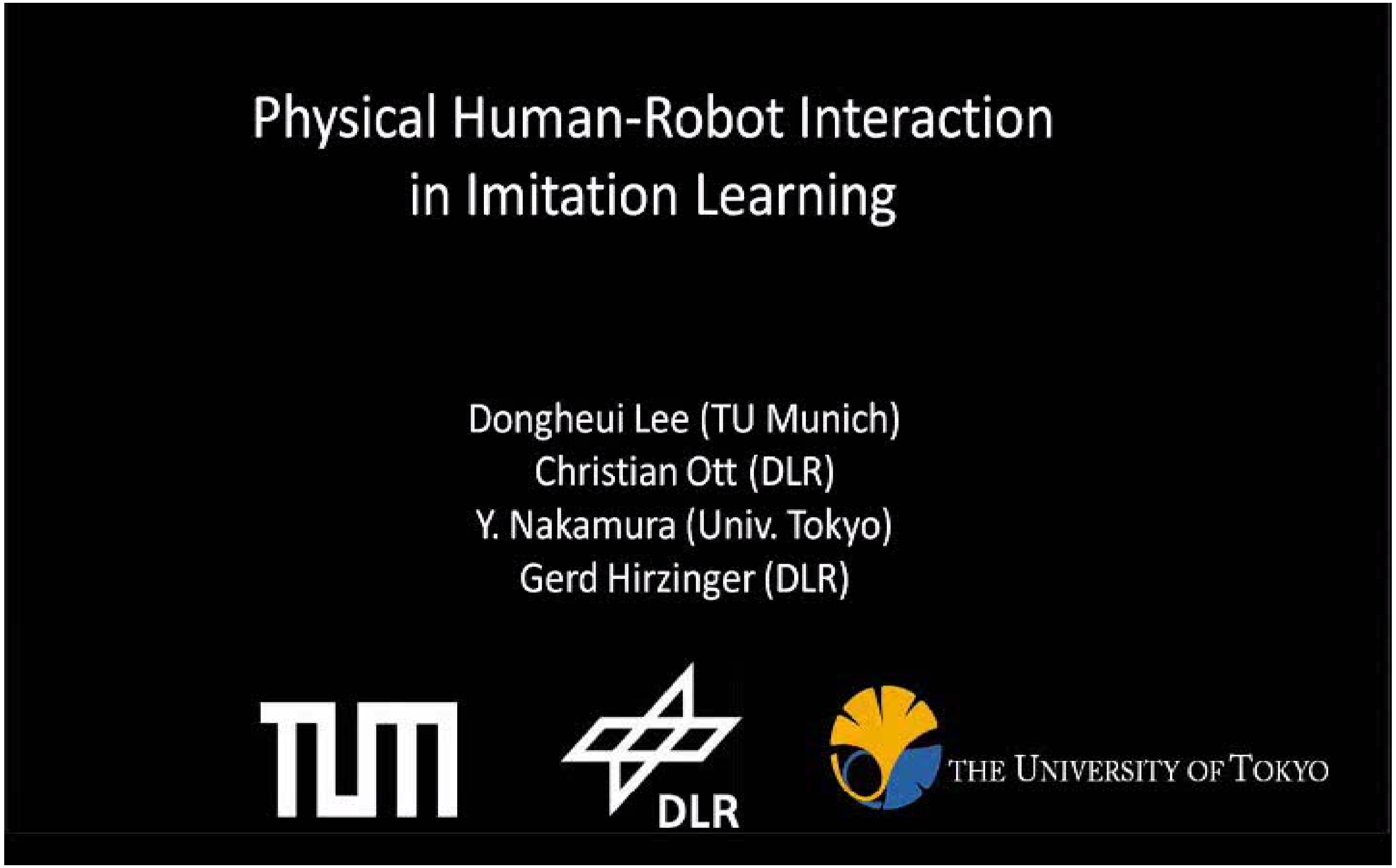
*Institute of Robotics and Mechatronics, German Aerospace Center (DLR e.V.)

**Department of Mechano-Informatics, University of Tokyo



This research is partly supported by Special Coordination Funds for Promoting Science and Technology, ”IRT Foundation to Support Man and Aging Society”.

IEEE ICRA2011 Video presentation

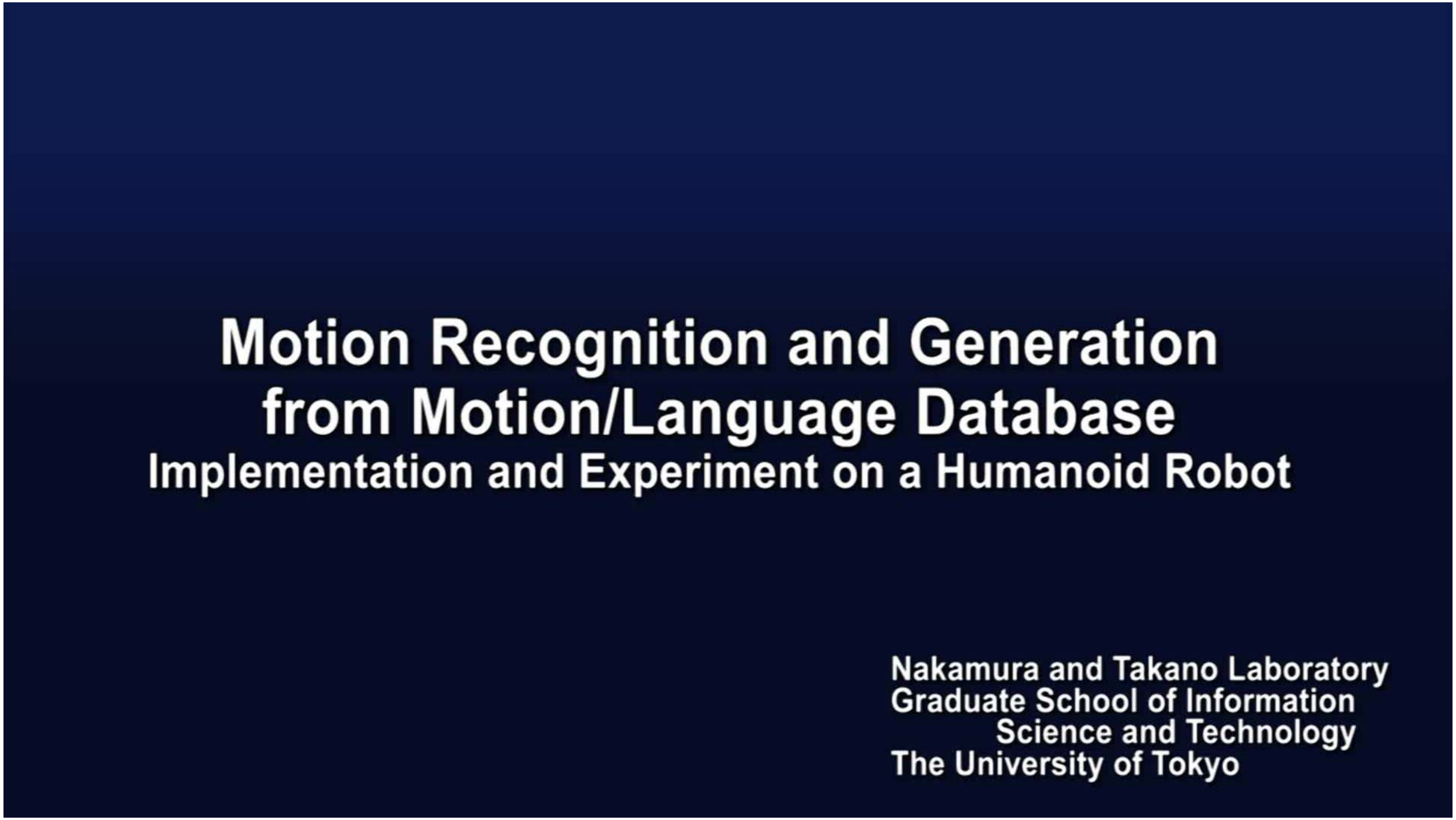


Physical Human-Robot Interaction in Imitation Learning

Dongheui Lee (TU Munich)
Christian Ott (DLR)
Y. Nakamura (Univ. Tokyo)
Gerd Hirzinger (DLR)

TUM
DLR
THE UNIVERSITY OF TOKYO

Including results of papers in ICRA2008 and 2009



Motion Recognition and Generation from Motion/Language Database

Implementation and Experiment on a Humanoid Robot

Nakamura and Takano Laboratory
Graduate School of Information
Science and Technology
The University of Tokyo

Challenges on actuators toward cognitive humanoids

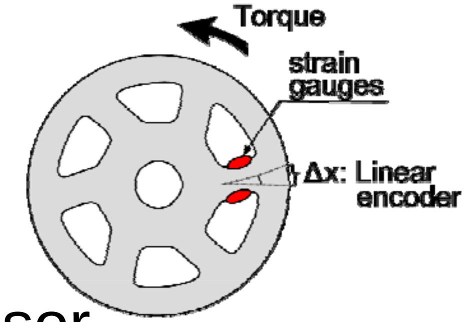
1. More power
2. Back drivability
3. Energy efficiency
4. High bandwidth (for human-humanoid physical interaction)

Torque Encoder

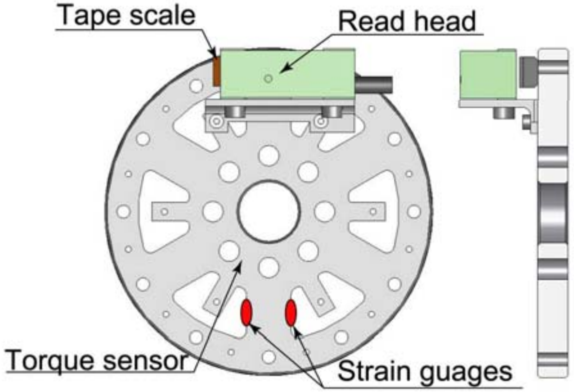
Tomohiro Kawakami, Ko Ayusawa, Hiroshi Kaminaga and Yoshihiko Nakamura, High-Fidelity Joint Drive System by Torque Feedback Control Using High Precision Linear Encoder, ICRA 2010.

Torque Encoder

1. Torque sensing method using linear encoders
    1. Features
        1. Noise immunity
        2. The ability to improve the resolution without changing the stiffness of the sensor
    2. Designs
        1. The local concentration of stress should not be caused.
        2. The nonuniform deformation should not be caused.
2. Locally-deformed torque sensor

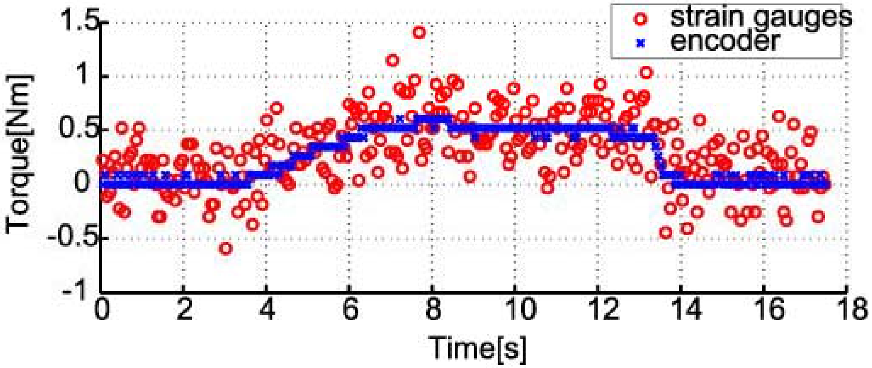


Torsional stiffness	3.0×10^5 [Nm/rad]
Measurement range	200[Nm]
Resolution	10[bit]
Safety factor	3
Material	A7075



Locally-deformed Torque Sensor

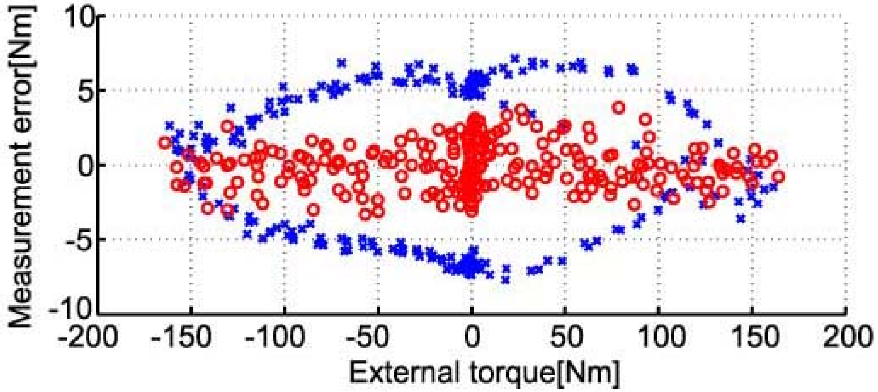
1. Evaluation of noise immunity
    1. Method: The input shaft was fixed and loaded with the external torque (0.5[Nm]).
    2. Results: Noise immunity was improved.



Standard deviation

Strain gauges: 2.3×10^{-1}[Nm]
Encoders: 5.5×10^{-2}[Nm]

2. Responses under high load condition
    1. Method: The input shaft was fixed and loaded slowly with the external torque in -160[Nm] to 160[Nm] range.
    2. Results：The hysteresis was ±7[Nm].

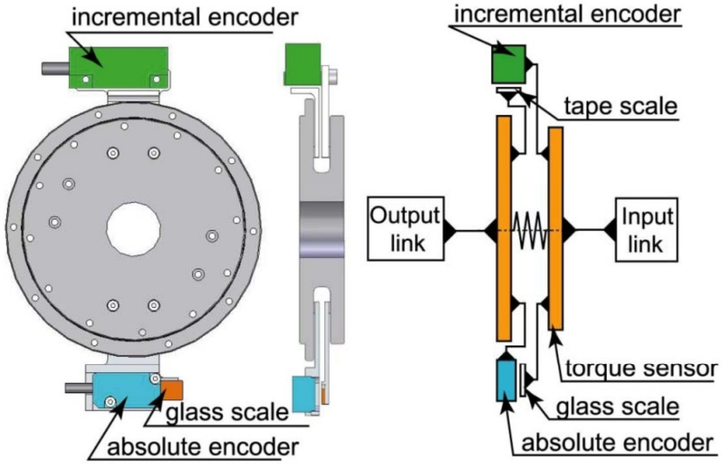


Development of Globally-deformed Torque Sensor

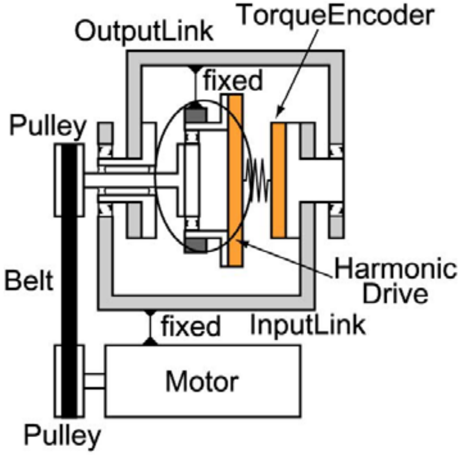
1. Sensors

1. Incremental linear encoder
   （Resolution: 10[nm]）
2. Absolute linear encoder
   （Resolution: 60[nm]）

Globally-deformed torque sensor



Joint Drive System

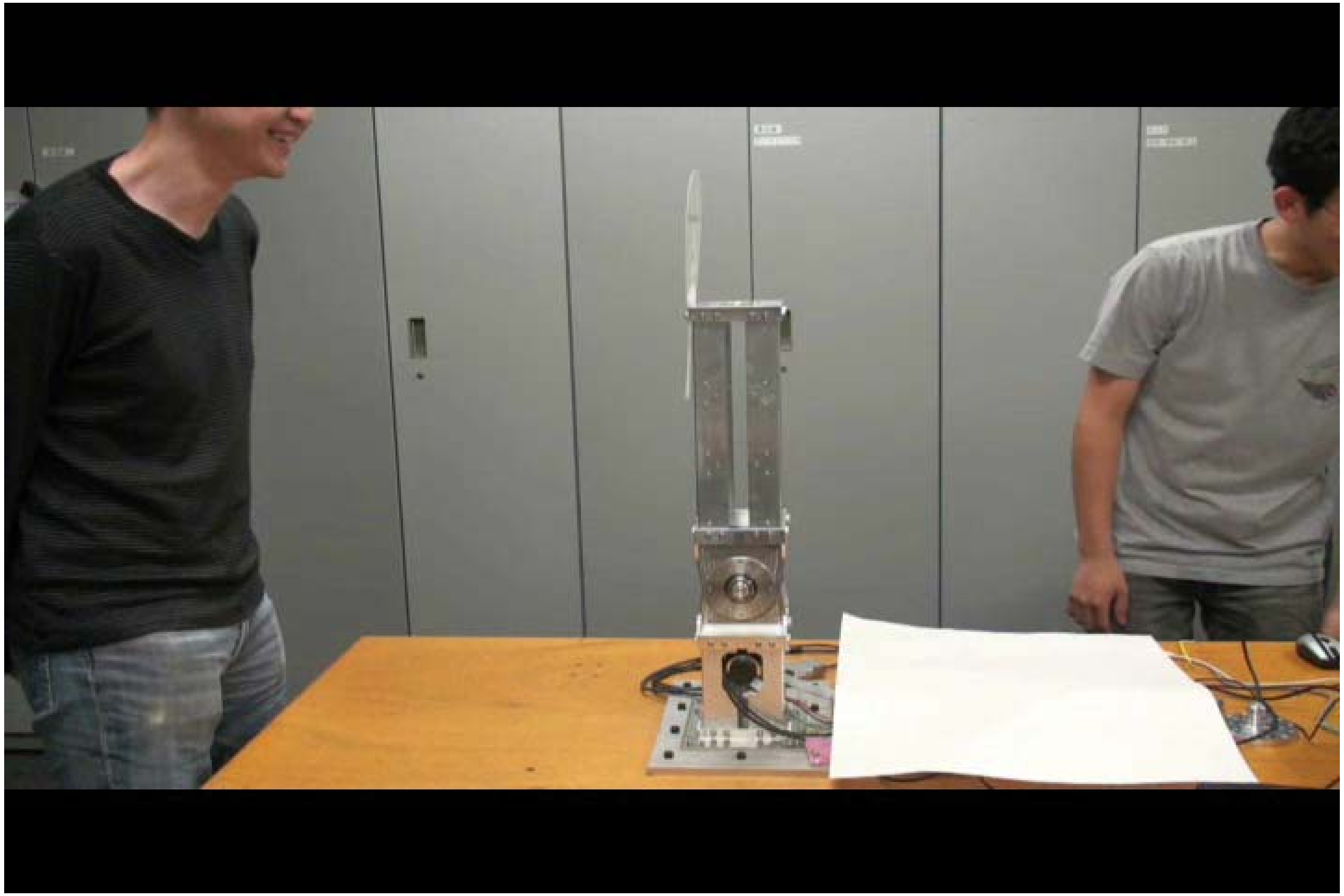


Torsional stiffness	3.0x10^{5}[Nm/rad]
Measurement range	200[Nm]
Resolution	10[bit]
Safety factor	9
Material	A7075

Local concentration is prevented without the reduction of the torsional stiffness and resolution.

Inertial Scaling

$$\tau_m = K_t\left(\tau_g - \tau_t\right) + \hat{\tau}_f$$



Takano and Nakamura Lab.
The University of Tokyo 2009

2 Joints Operation with Gravity Compensation

Nakamura and Takano Lab.
The University of Tokyo, 2009

High-Fidelity Rigid Digital Torque Encoder

Y. Nakamura, H. Kaminaga, K. Ayusawa and T. Kawakami

Nov. 18, 2009

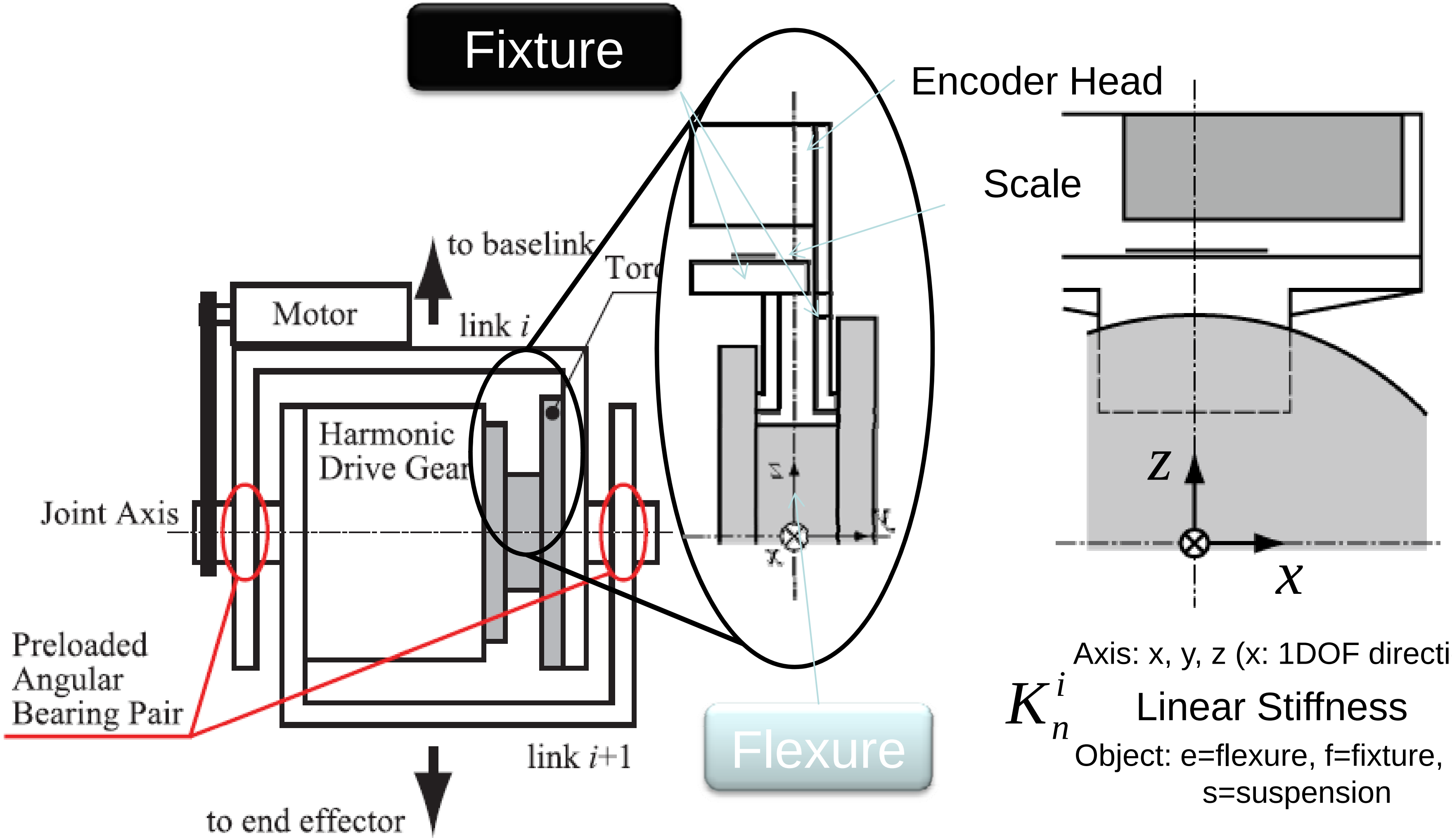
IRT Humanoid Robot Project

H. Kaminaga, K. Odanaka, T. Kawakami, and Y. Nakamura

Measurement Crosstalk Elimination of Torque Encoder Using Selectively Compliant Suspension

IEEE ICRA 2011.

Basic Structure of Torque Encoder



Fixture

Encoder Head

Scale

Flexure

Axis: x, y, z (x: 1DOF direction)

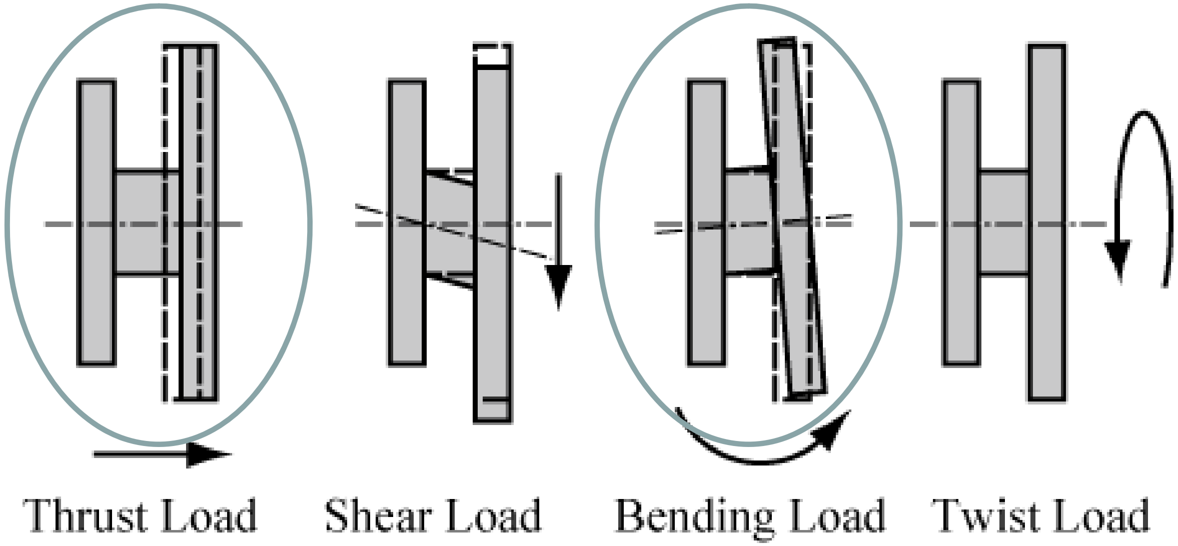
K_n^i Linear Stiffness

Object: e=flexure, f=fixture, s=suspension

Axis: x, y, z (y: 1DOF direction)

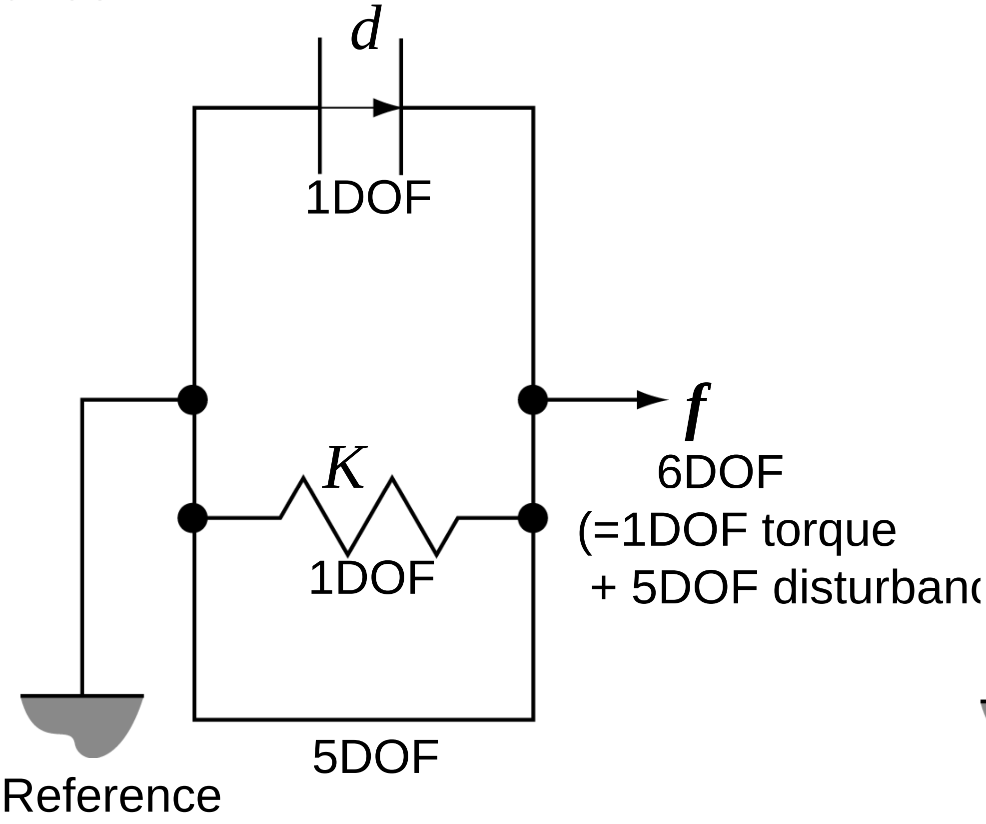
G_n^i Torsional Stiffness

Deformation Modes

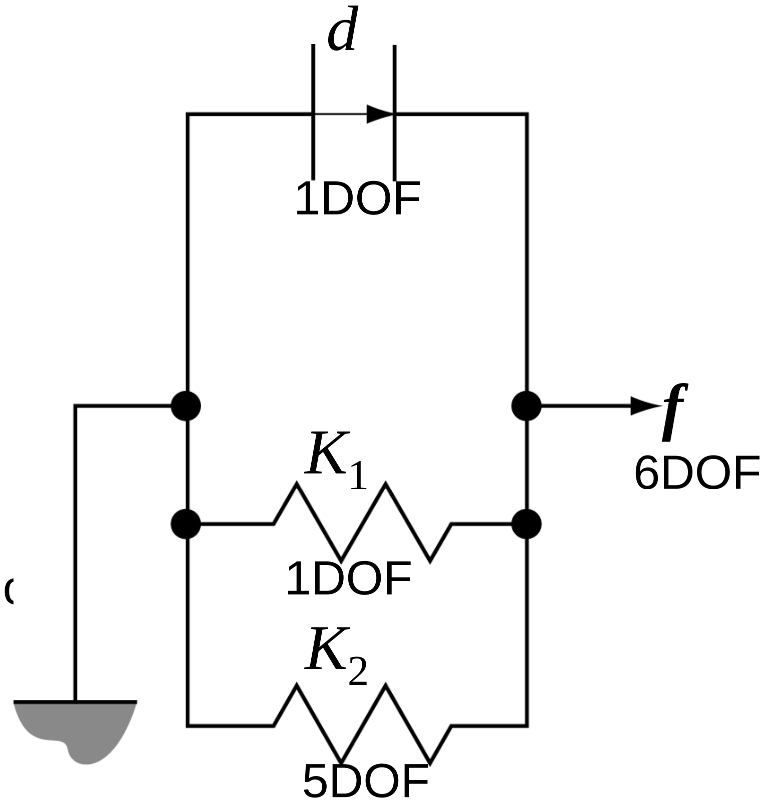


Measurement Crosstalk

Crosstalk: Measurement interference between different measurement axes

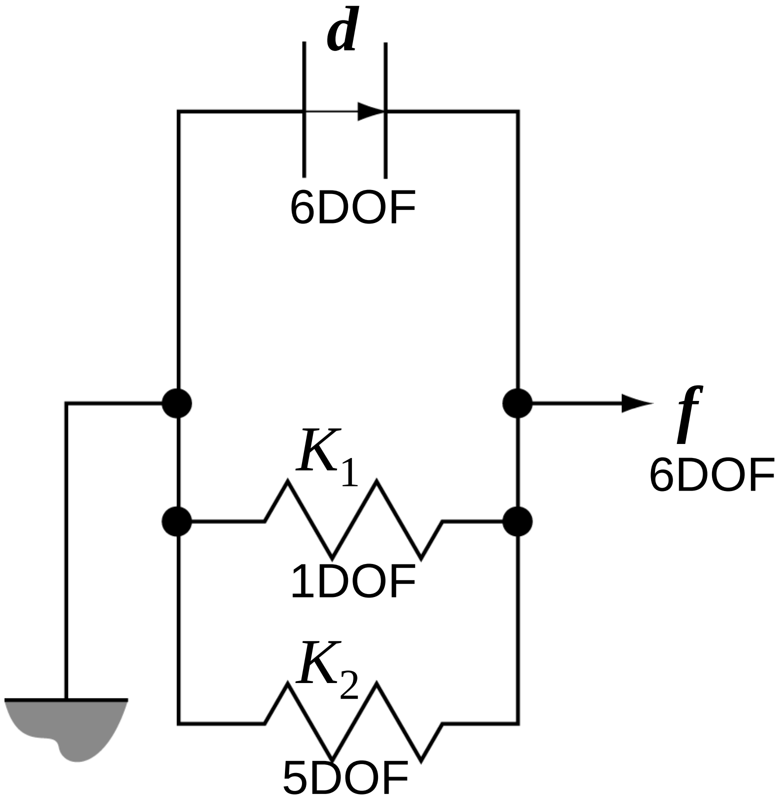


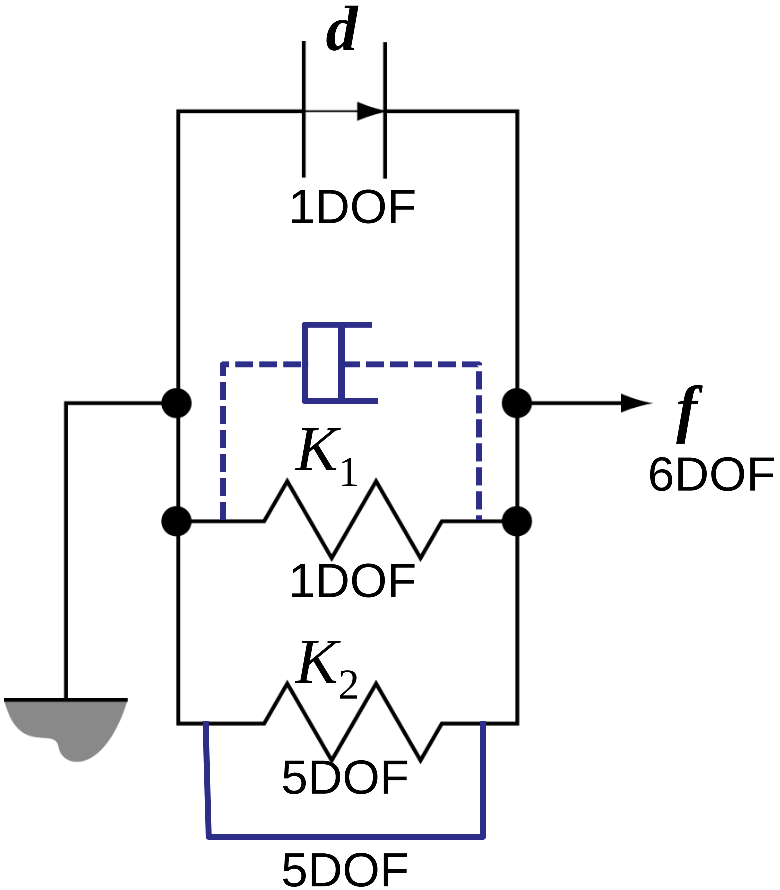
Ideal Case



Reality

Solution for Crosstalk Suppression



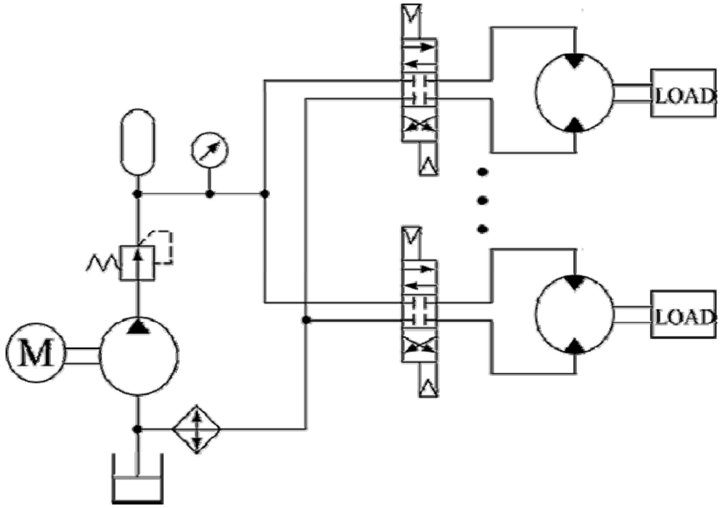


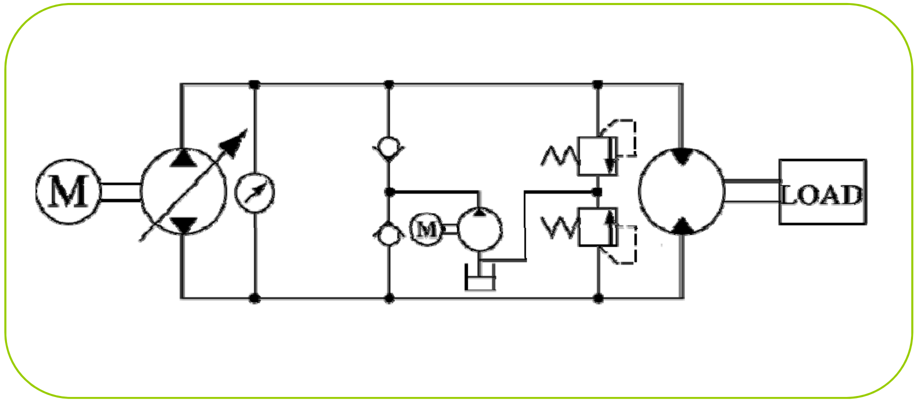
Pro: no additional source of disturbance
Con: bulky, more processing necessary

Pro: no additional sensor necessary
Con: possibility of additional disturbance as friction

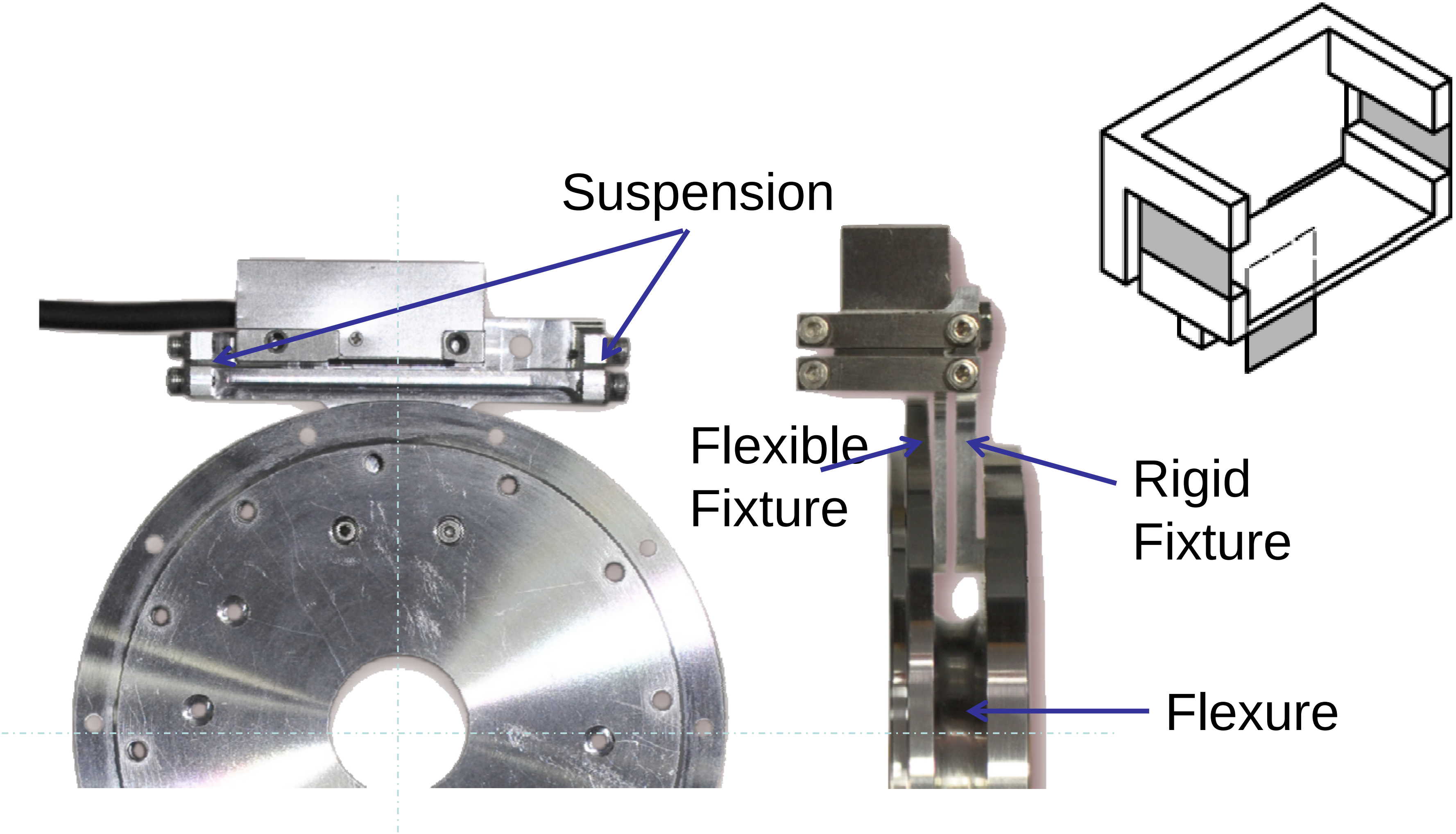
Electro-Hydrostatic Actuator

1. A class of hydraulic actuator that control rotation of hydraulic motor by controlling pump displacement
2. Core component: Hydrostatic Transmission





Proposed Implementation



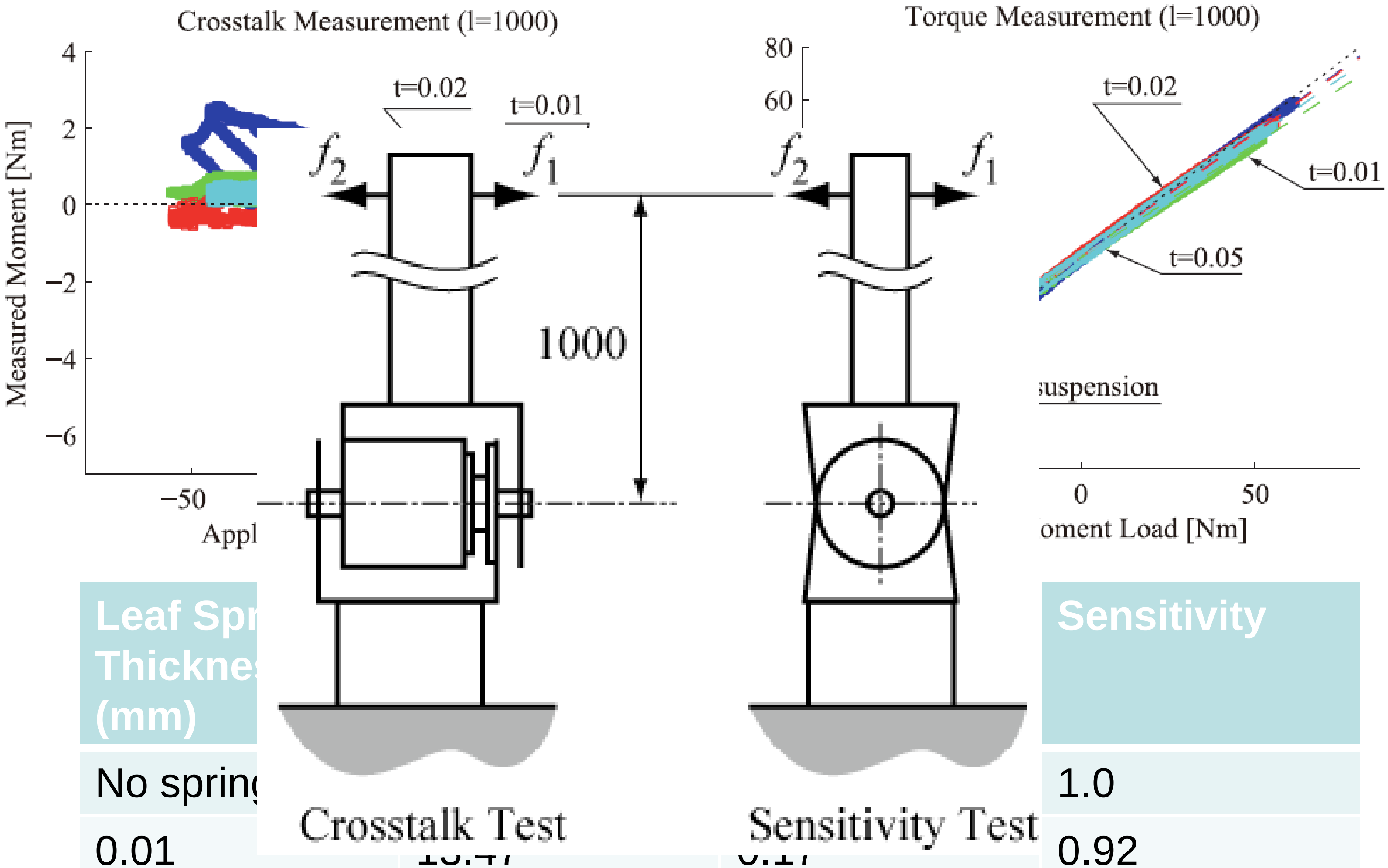
Suspension

Flexible Fixture

Rigid Fixture

Flexure

Experiment



Leaf Spr Thickne (mm)			Sensitivity
No sprin			1.0
0.01	[illegible]	[illegible]	0.92
0.02	107.8	0.21	0.94
0.05	1684	0.15	0.91

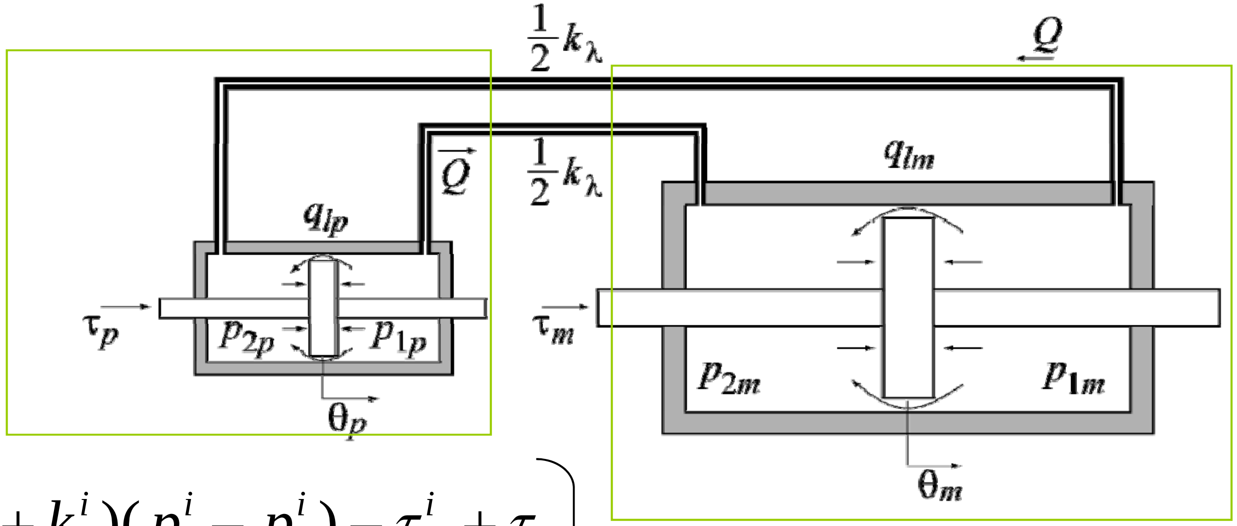
3DOF Manipulator with Crosstalk-free Torque Encoders Gravity and Friction Compensated

3DOF Manipulator with Crosstalk-free Torque Encoders
Gravity and Friction Compensated and Impedance Controled

Electro-Hydrostatic Actuator

Hiroshi Kaminaga, Taichi Yamamoto, Junya Ono, and Yoshihiko Nakamura,Backdrivable Miniature Hydrostatic Transmission for Actuation of Anthropomorphic Robot Hands, IEEE Humanoid 2007.

Simplified Model of EHA



$$\left.\begin{aligned}
J_i\ddot{\theta}_i &= -(k_t^i + k_q^i)(p_1^i - p_2^i) - \tau_f^i + \tau_i \\
p_2^i &= p_1^i - \frac{1}{2}k_\lambda Q \\
Q &= k_d^i\dot{\theta}_i - k_l^i(p_1^i - p_2^i)
\end{aligned}\right\} \longrightarrow \quad
\begin{aligned}
&J_i\ddot{\theta}_i = -k_3^i(k_1^i\dot{\theta}_i - k_2^i\dot{\theta}_{\bar{i}}) - \tau_f^i + \tau_i \\
&(i,\bar{i}) \in \{(p,m),(m,p)\}
\end{aligned}$$

$$\begin{bmatrix} J_p & 0 \\ 0 & J_m \end{bmatrix}\begin{bmatrix} \ddot{\theta}_p \\ \ddot{\theta}_m \end{bmatrix} = \begin{bmatrix} -k_1^p k_3^p & k_2^p k_3^p \\ k_2^m k_3^m & -k_1^m k_3^m \end{bmatrix}\begin{bmatrix} \dot{\theta}_p \\ \dot{\theta}_m \end{bmatrix} - \begin{bmatrix} \tau_f^p \\ \tau_f^m \end{bmatrix} + \begin{bmatrix} \tau_p \\ \tau_m \end{bmatrix}$$

Miniature Electro-Hydrostatic Actuator and Anthropomorphic Robot Hand

H. Kaminaga, T. Yamamoto, J. Ono, and Y. Nakamura,“Anthropomorphic Robot Hand with Hydrostatic Actuators,” Proc. of 25th Annual Conf. of the Robotics Society of Japan, 1L17 (2007).

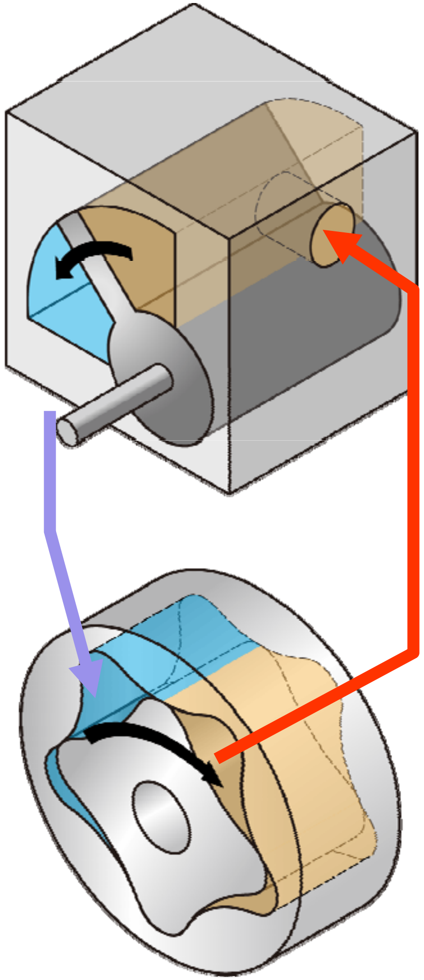
H. Kaminaga, T. Yamamoto, J. Ono, and Y. Nakamura, “Anthropomorphic Robot Hand With Hydrostatic Actuators”, Proc. of 7th IEEE-RAS Int’l Conf. on Humanoid Robots (2007).

H. Kaminaga, J. Ono, T. Yamamoto, and Y. Nakamura, “New Robot Actuator Using Hydrostatic Transmission”, Proc. of Robotics Symposia, 113-118(2008).

Requirements on Miniature EHA

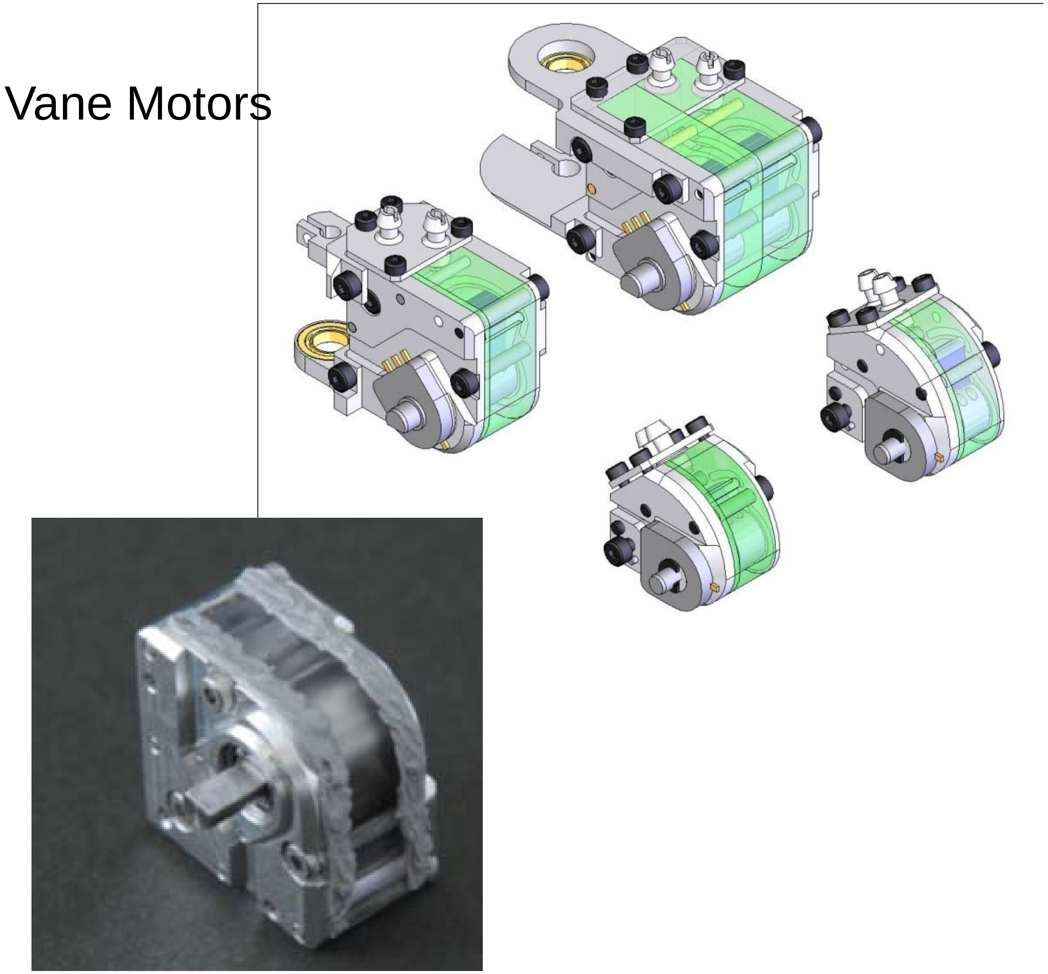
1. Backdrivable structure
2. Large output torque
   (large displacement ratio)
3. Mechanically Simple
   (esp. for robot hand)
4. Rotary Output

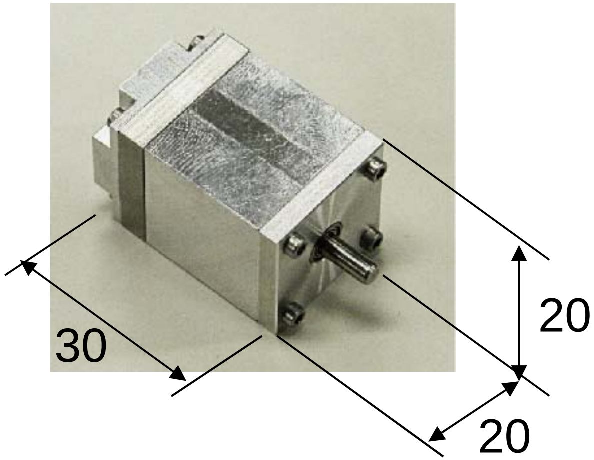
Trochoid Pump + Vane Motor



Miniature EHA

Vane Motors

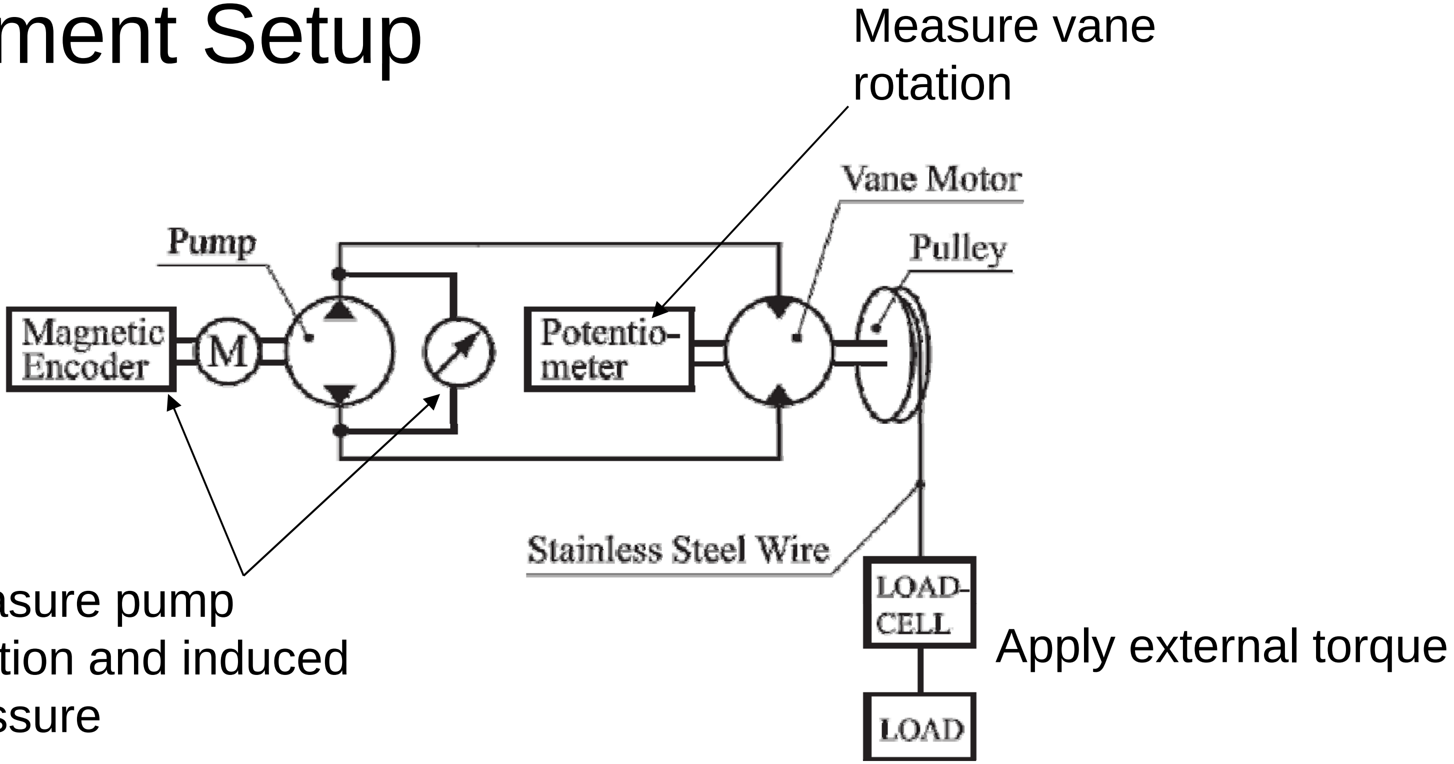




Trochoid Pump Head

Experiment: Backdrivability

Experiment Setup

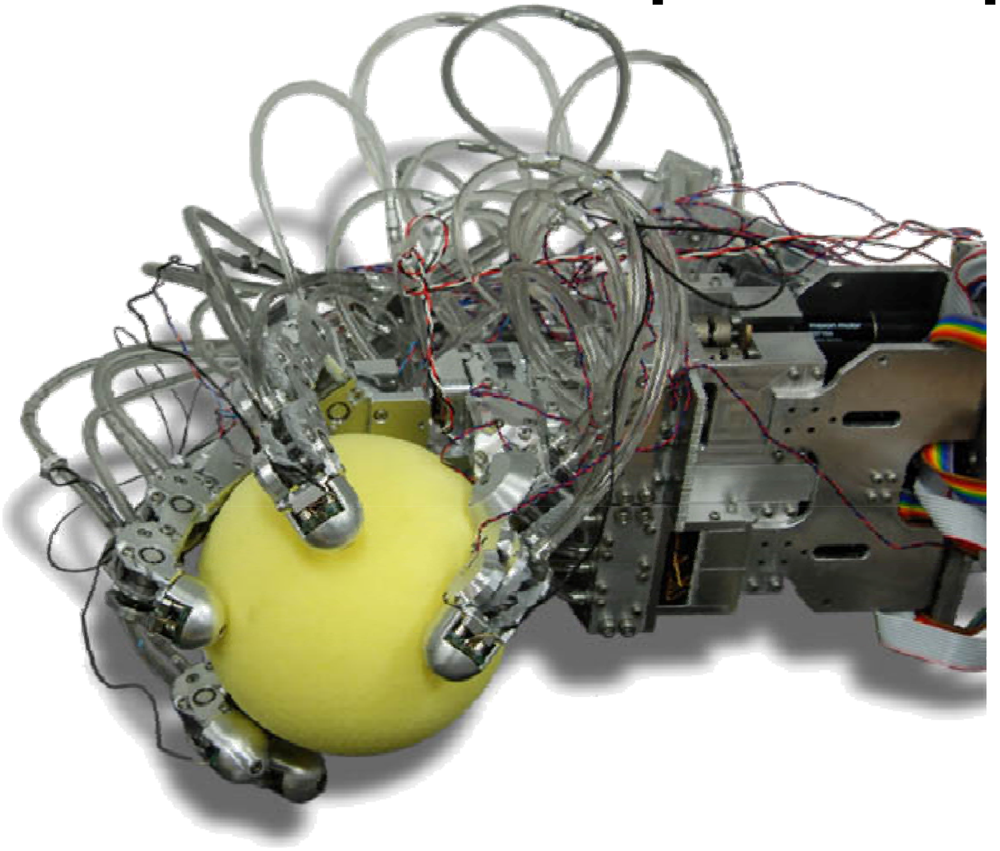


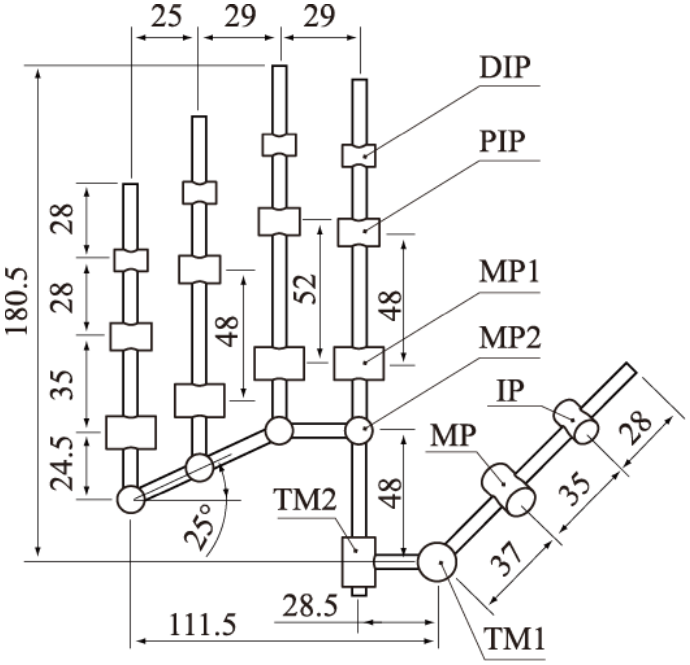
Measure vane rotation

Measure pump rotation and induced pressure

Apply external torque

Anthropomorphic Hand

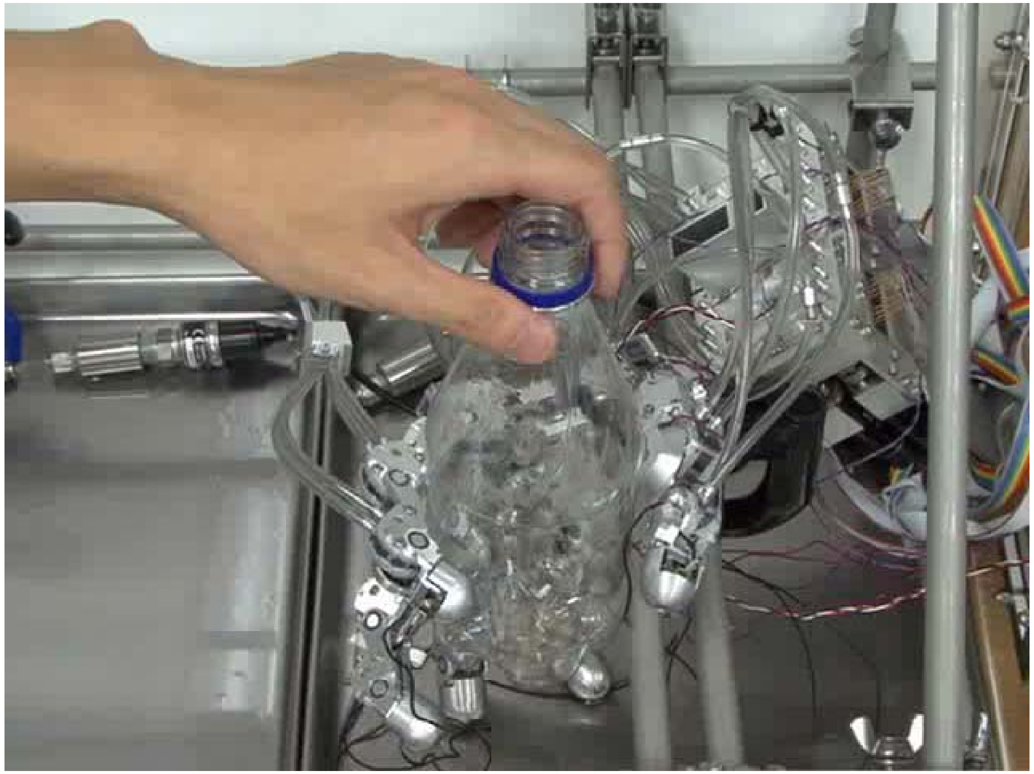


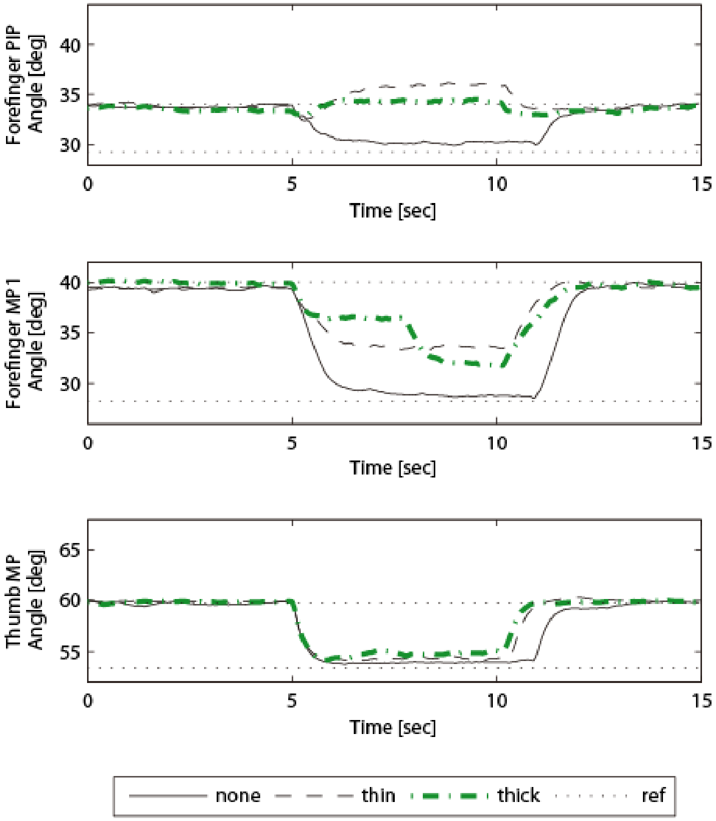


Weight (Hand)	700g
Weight (Forearm)	3,000g
DOF	20 (16 independent)
Hydraulic Oil	Silicon Oil

T. Yamamoto, “Anthropomorphic Robot Hand with Valveless Hydraulic Actuation,” Master Thesis of The University of Tokyo, 2007.

Experiment: Blind Grasping



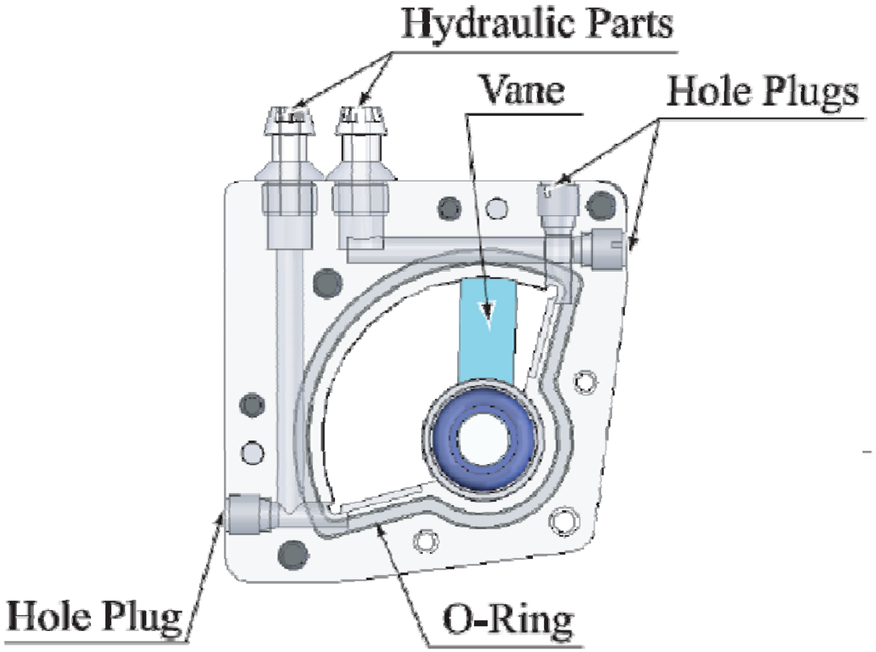


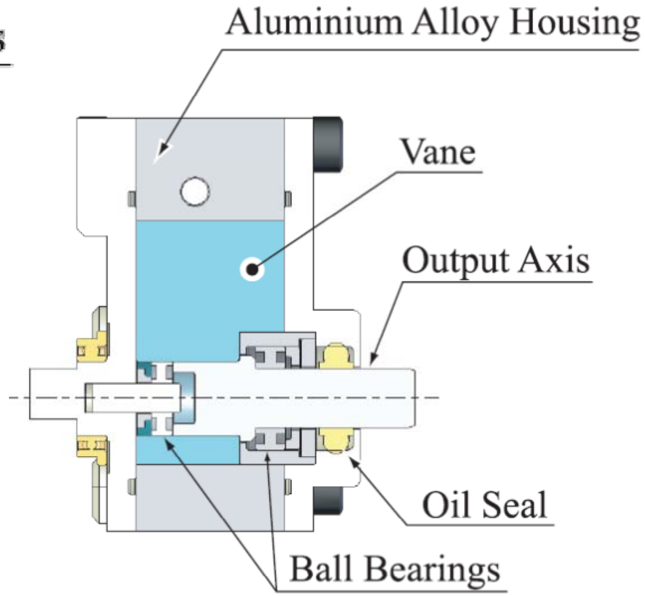
Hiroshi Kaminaga, Junya Ono, Yuto Shimoyama,
Tomoya Amari, Yukihiro Katayama, and Yoshihiko Nakamura

Anthropomorphic Robot Hand with Hydrostatic Cluster Actuator and Detachable Passive Wire Mechanism

IEEE Humanoid 2009.

Vane Motor with Enhanced Machining Precision and Rigidity



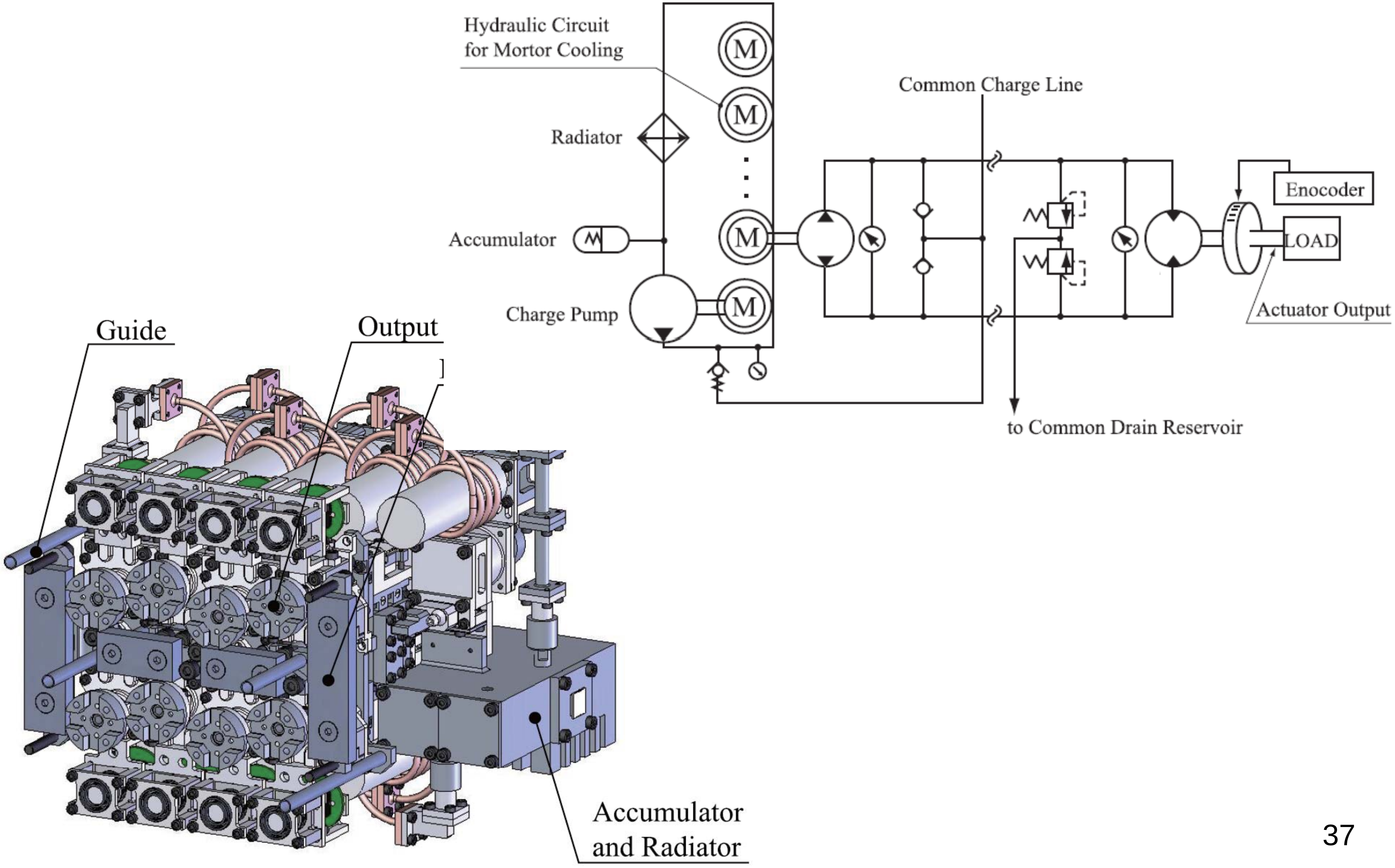


-Metal casing with built-in channel
-Support of vane axis both ends by ball bearings with preloading
-O-Ring seal to prevent external leakage

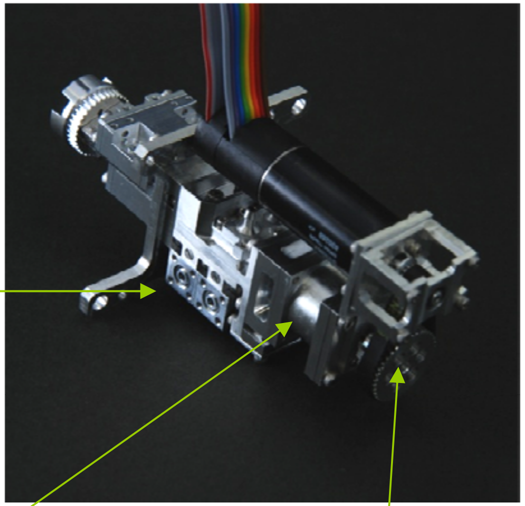
J. Ono, H. Kaminaga, and Y. Nakamura, “HST with Anti-Cavitation Mechanism for Miniature Robot Actuator. In Proc. of Robomec 2008, volume DVD-ROM, pages 1A1–B23, 2008. in Japanese.

Description	Value
Inner Radius (r_m)	4.5 (mm)
Outer Radius (r_M)	12 (mm)
Vane Width (b^m)	10 (mm)
Vane Thickness (w^m)	4 (mm)
Motion Range	120 (deg)

Cluster EHA (Ono 2009)



Directly Coupled EHA Module

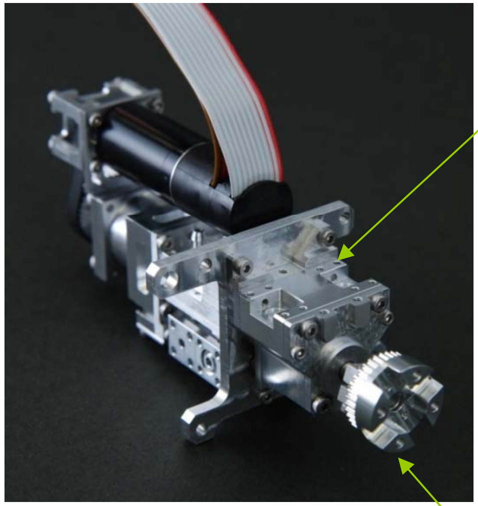


Charge
And
Relief Valves

Trochoid Pump

Belt Pre-Reducer

Rear View

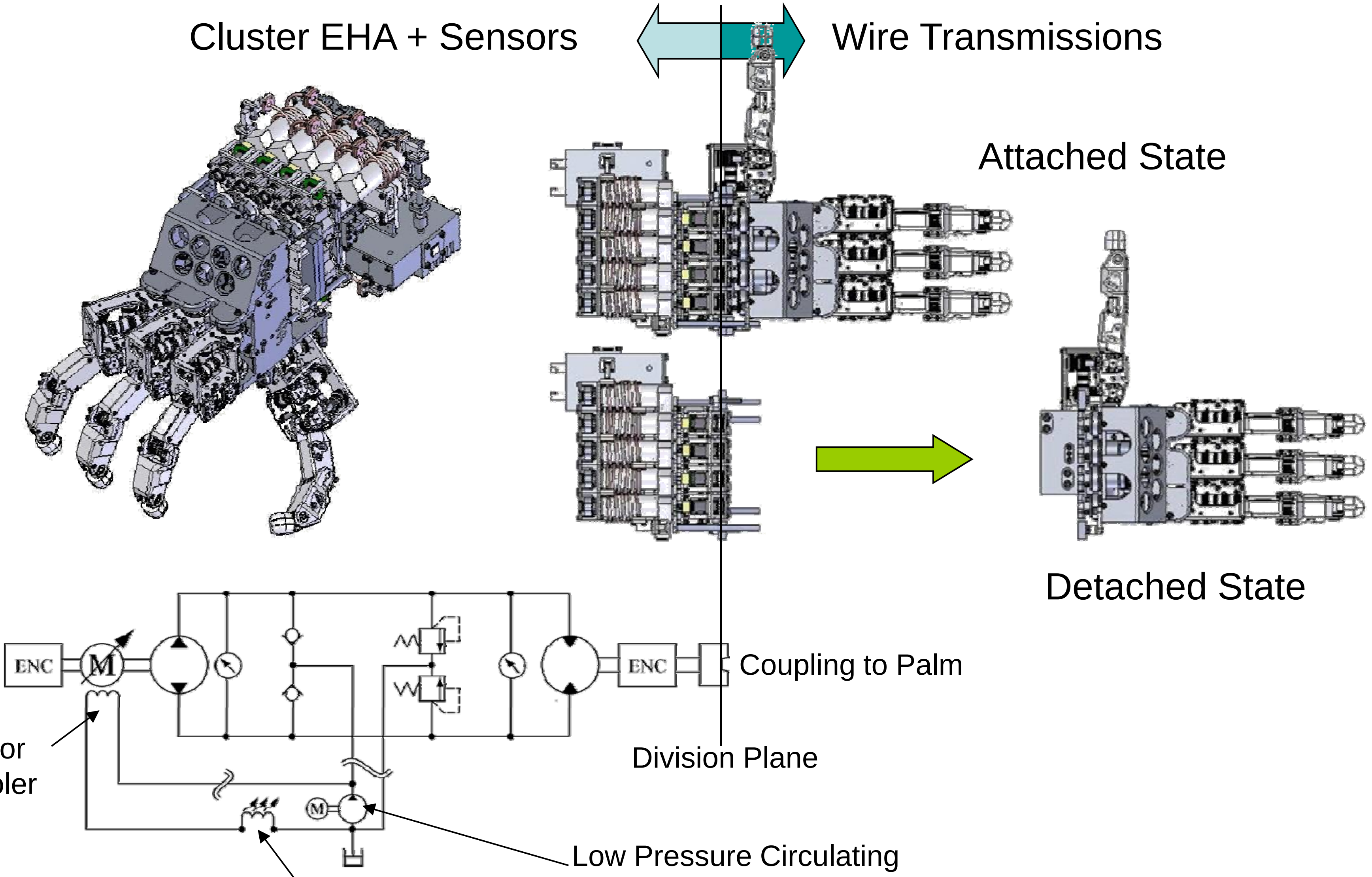


Vane Motor

Backlashless
Coupling

Front View

Detached State and Functionality Division



Cluster EHA + Sensors

Wire Transmissions

Attached State

Detached State

Coupling to Palm

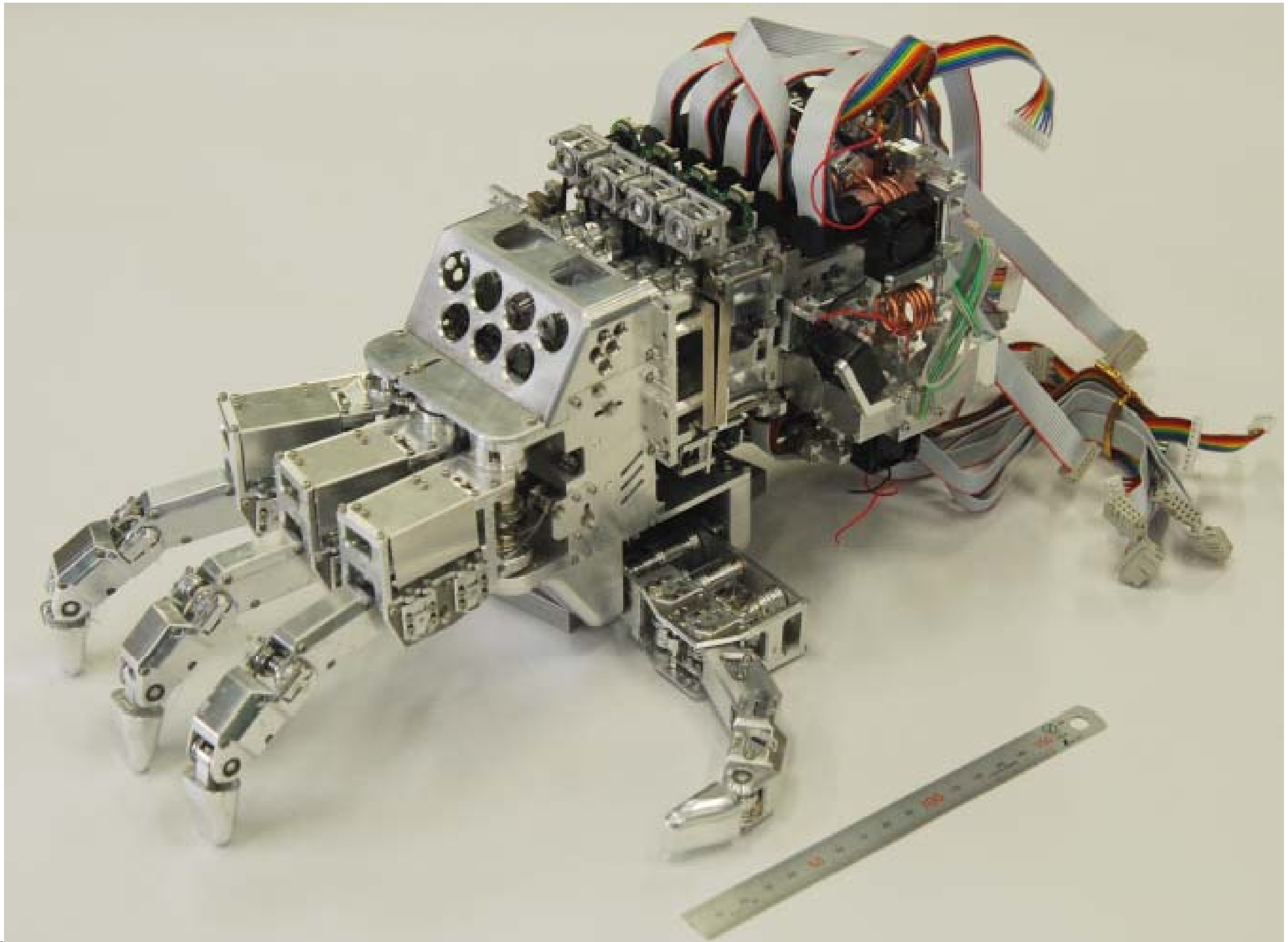
Division Plane

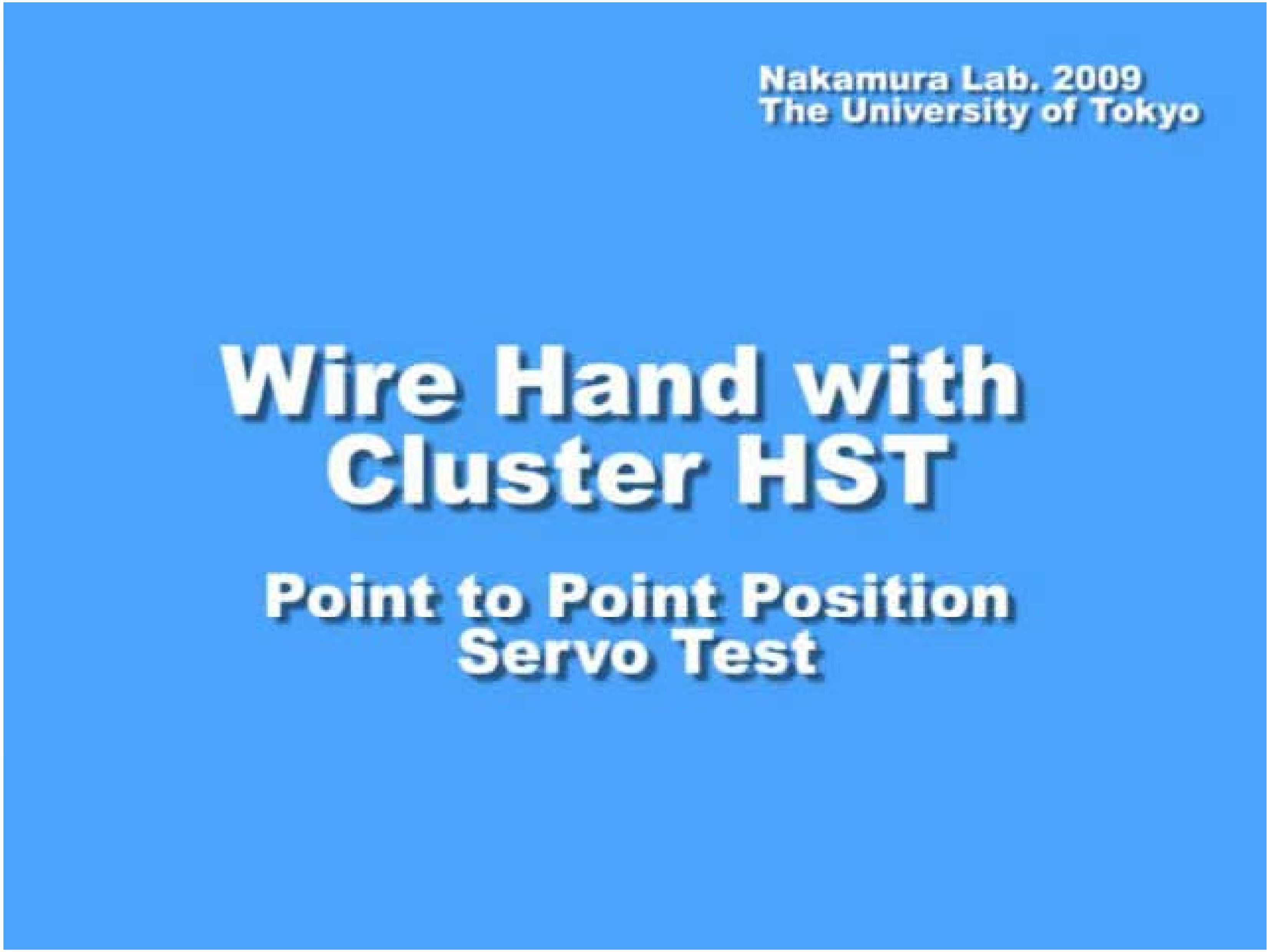
Motor
Cooler

Radiator

Low Pressure Circulating
And Charging Pump
(Central)

Outlook of the Hand





Nakamura Lab. 2009
The University of Tokyo

Wire Hand with Cluster HST

Point to Point Position Servo Test

Hiroshi Kaminaga, Junya Ono, Yusuke Nakashima, and Yoshihiko Nakamura

Development of Backdrivable Hydraulic Joint Mechanism for Knee Joint of Humanoid Robots

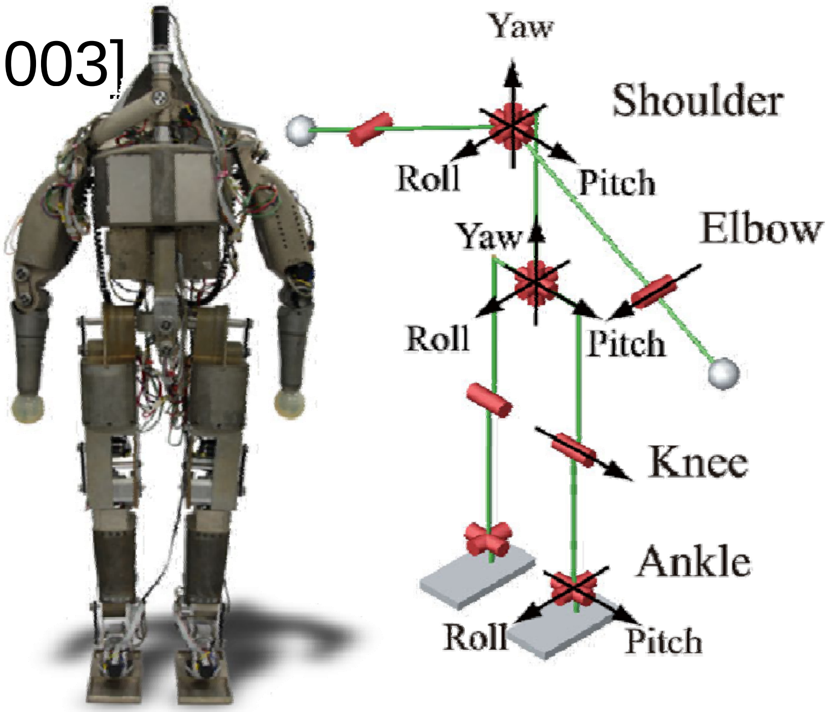
IEEE ICRA2009.

Mass Property of the Robot Used for Specification Calculation

1. UT-θ2 [Yamamoto et al. 2003]

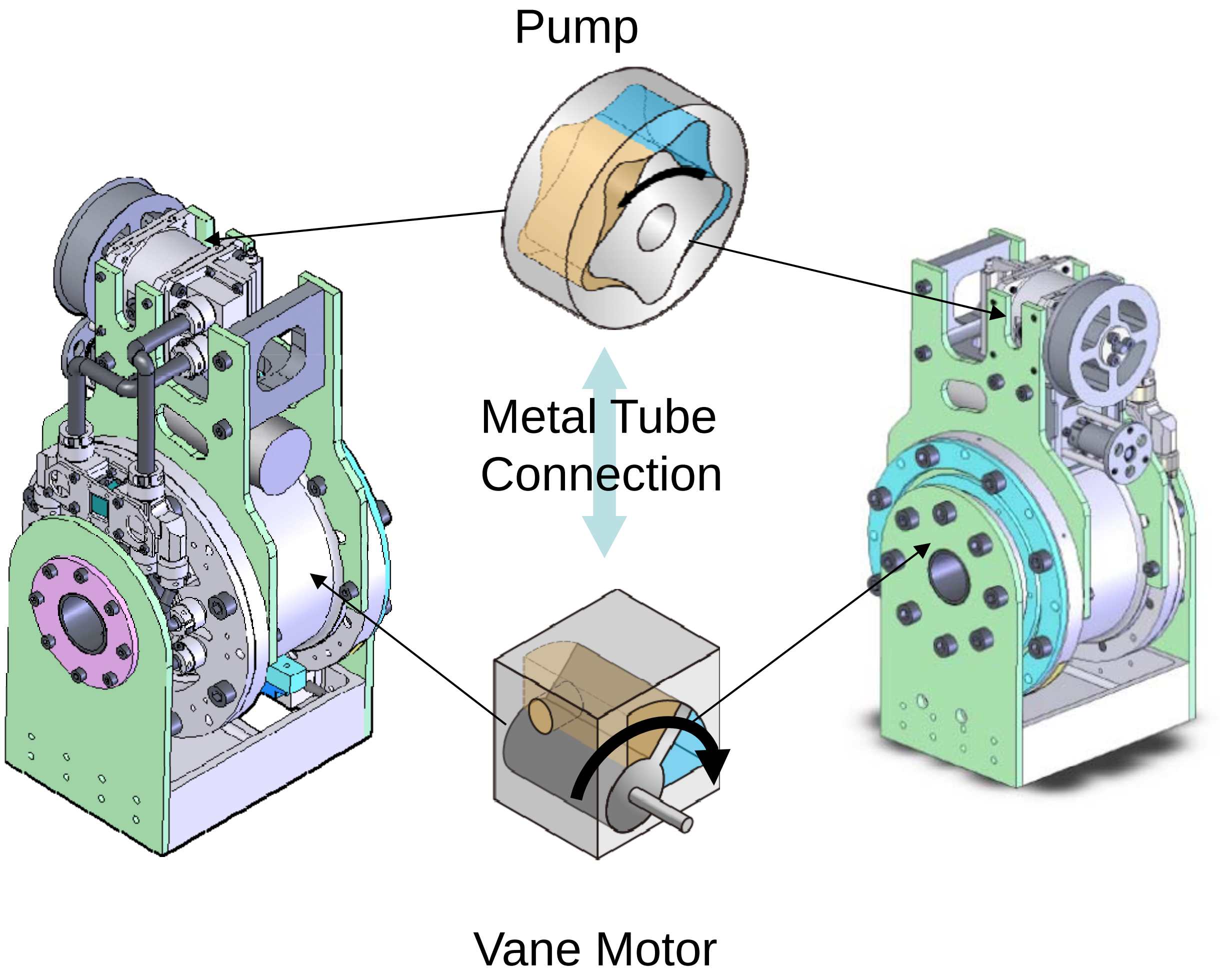
Task Requirement:

Forward walk with step length of 300(mm) with period 0.8(sec) calculated with boundary condition relaxation [Sugihara and Nakamura 2005]



DOF	20
Height	1500(mm)
Weight	45(kg)
Joint Drive Mehcanism	DC Motor + Harmonic Drives

Designed Knee Joint



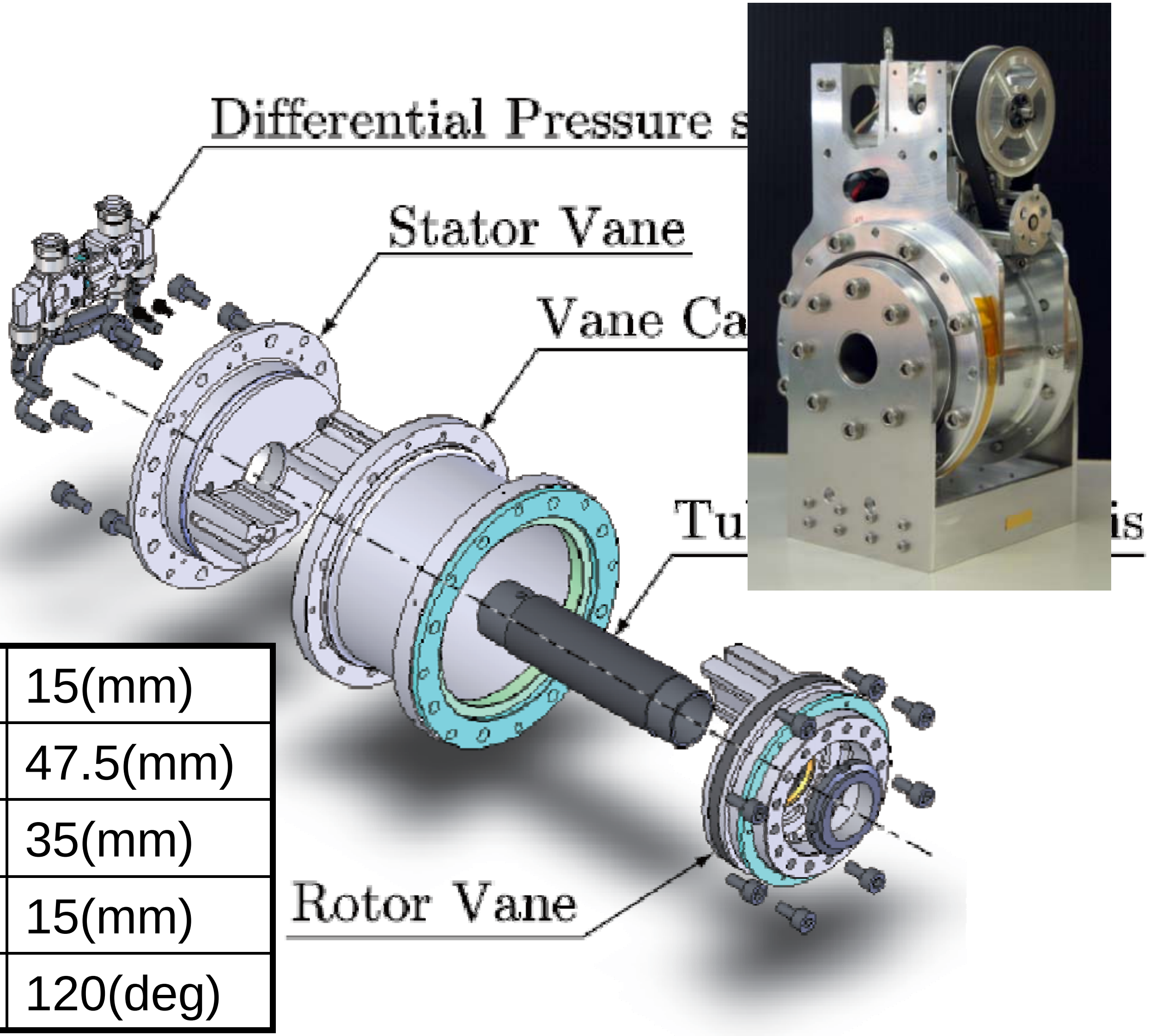
Pump

Metal Tube Connection

Vane Motor

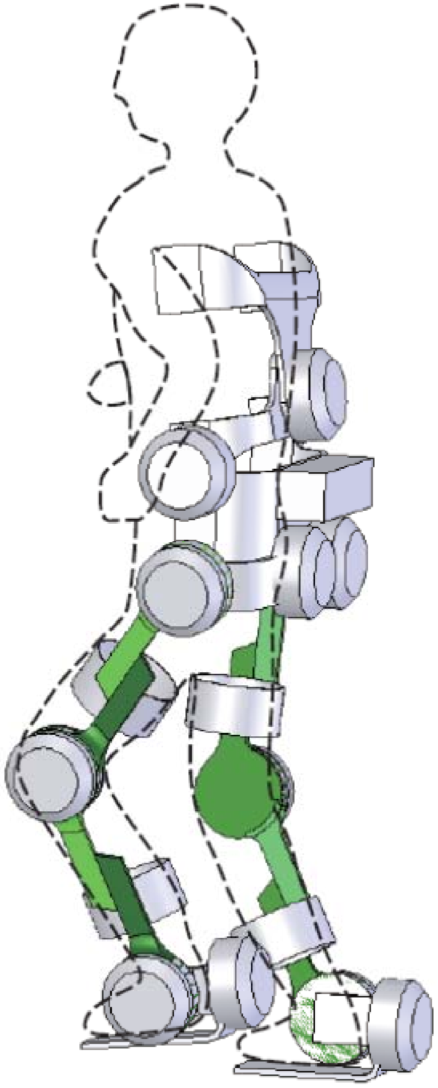
Actuator Architecture

1. Axis symmetric architecture
2. Flange output
3. Tubular axis



Inner Radius (r_m)	15(mm)
Outer Radius (r_M)	47.5(mm)
Vane Width (b^m)	35(mm)
Vane Thickness (w^m)	15(mm)
Motion Range	120(deg)

Lower Extremity Exoskeleton



1. Improvement of QOL of elderly by providing means of locomotion

2. Objective
   - Quantitative methodology to decide necessary performance
   - Force sensitive and backdrivable structure
   - Reliable Structure

3. Whole locomotion pattern is considered
   - Not only walking
   - Stand up – walk – sit down

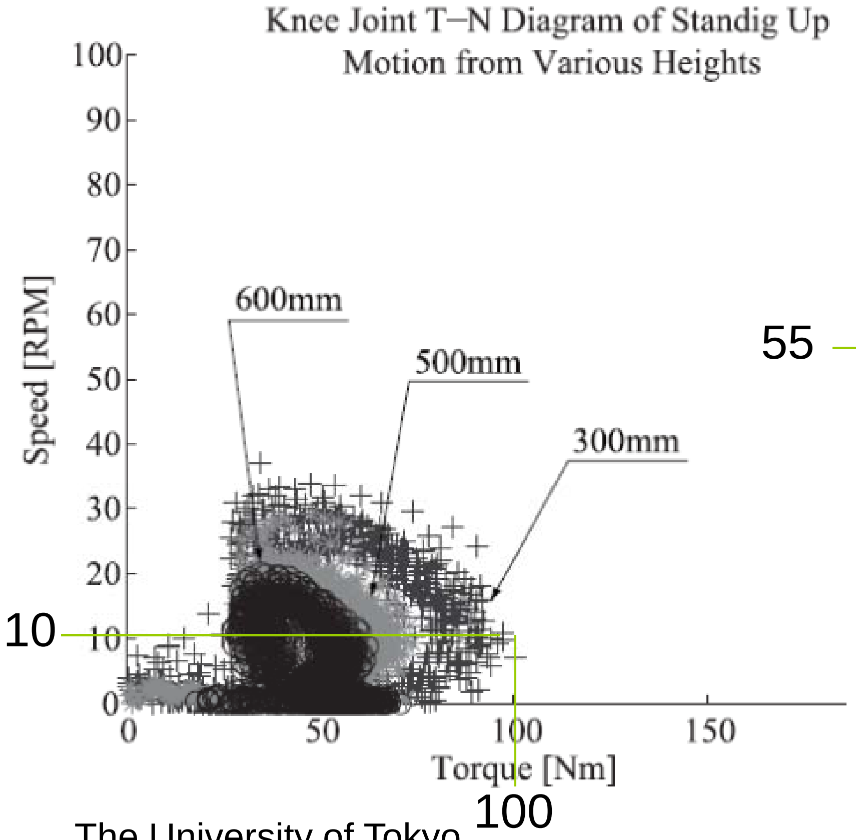
4. Design goal

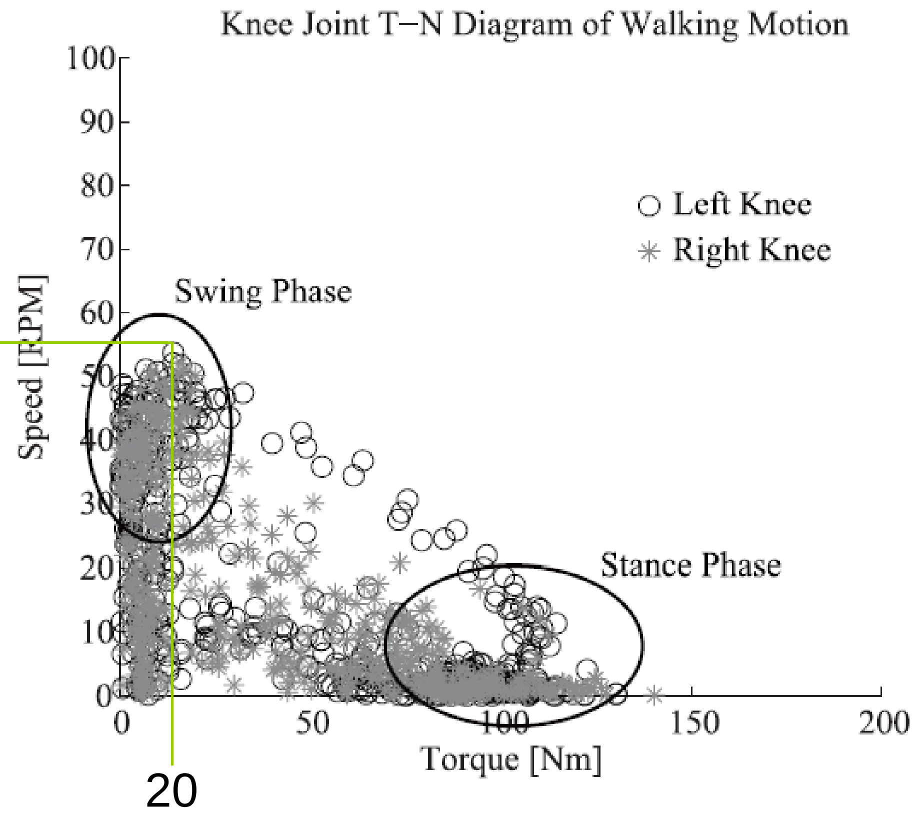
   Give support that vast majority of healthy elderly can score > 10 in CS-30 test

Previous Works: (Pratt et al. 2004) (Kazerooni et al. 2005) (Hayashi et al. 2005)

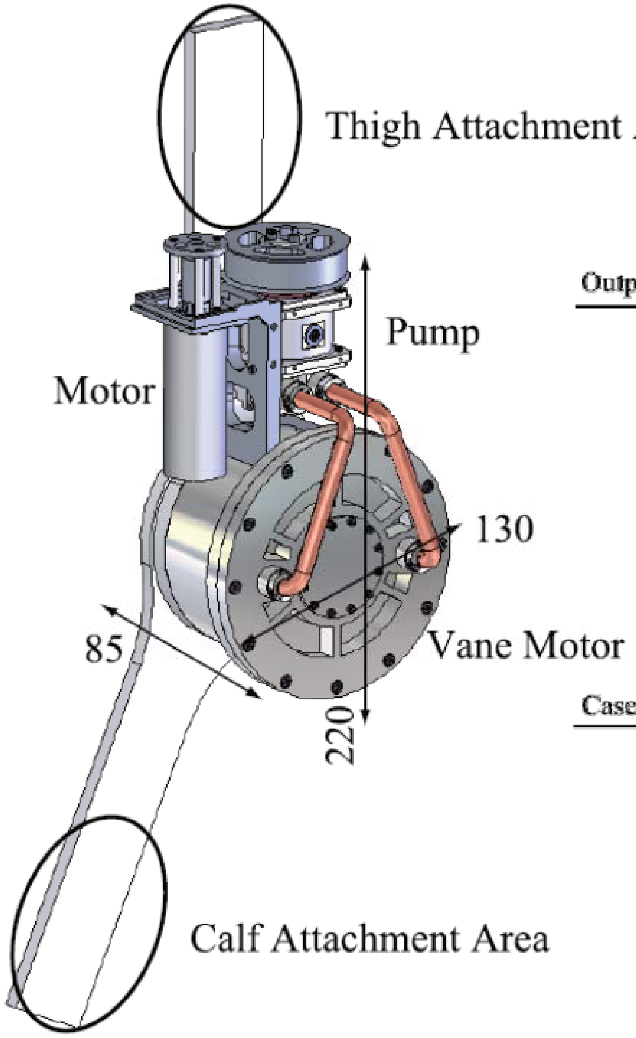
Torque and Speed Requirement

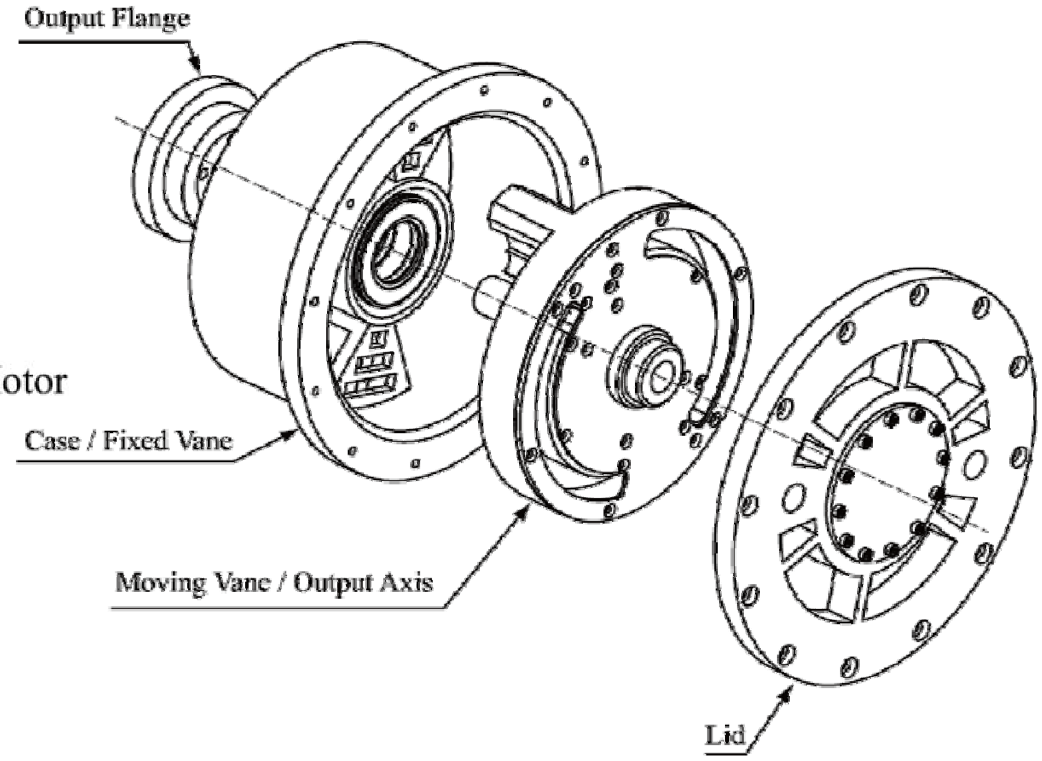
Inverse dynamics result of human figure with 71kg body mass for the data optically captured healthy subject





Outlook of Designed Knee Joint

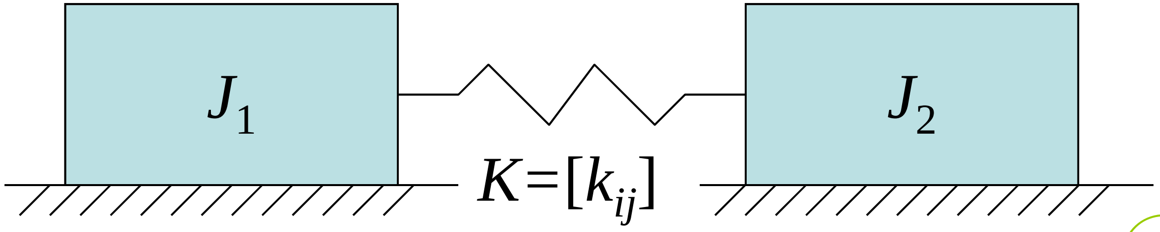




Conceptual Models

1. Series Elastic Actuator

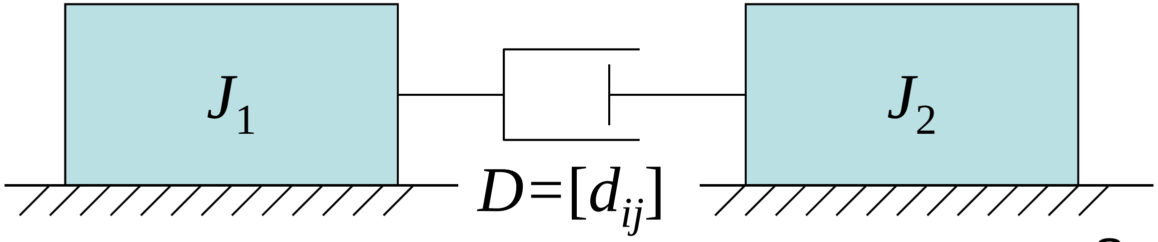
System is 2nd order



<u>output backdrivability</u> is obtained by dynamics decoupling

- Series Dissipative Actuator

[ICRA2010]



System is 1st order

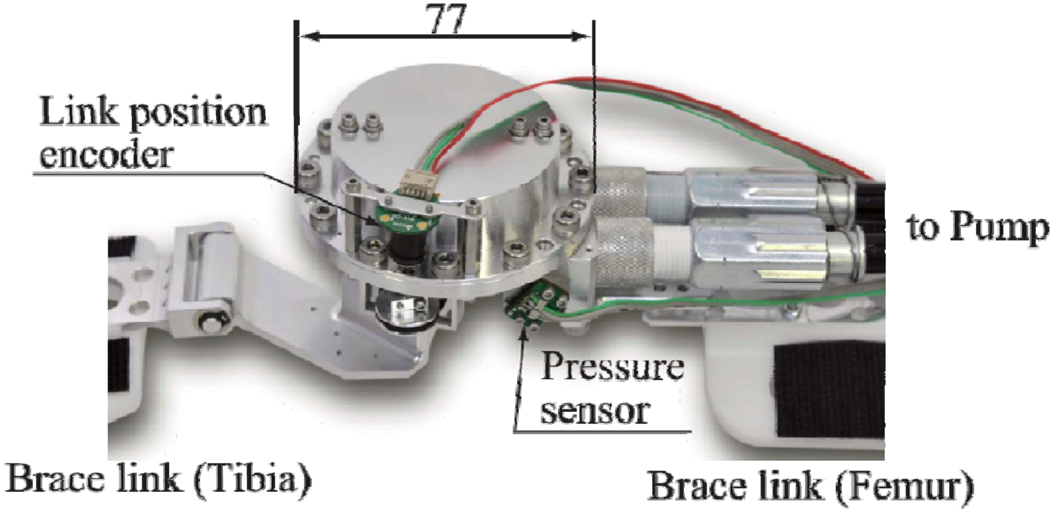
Series damping actuator [Chew et al. 2004]

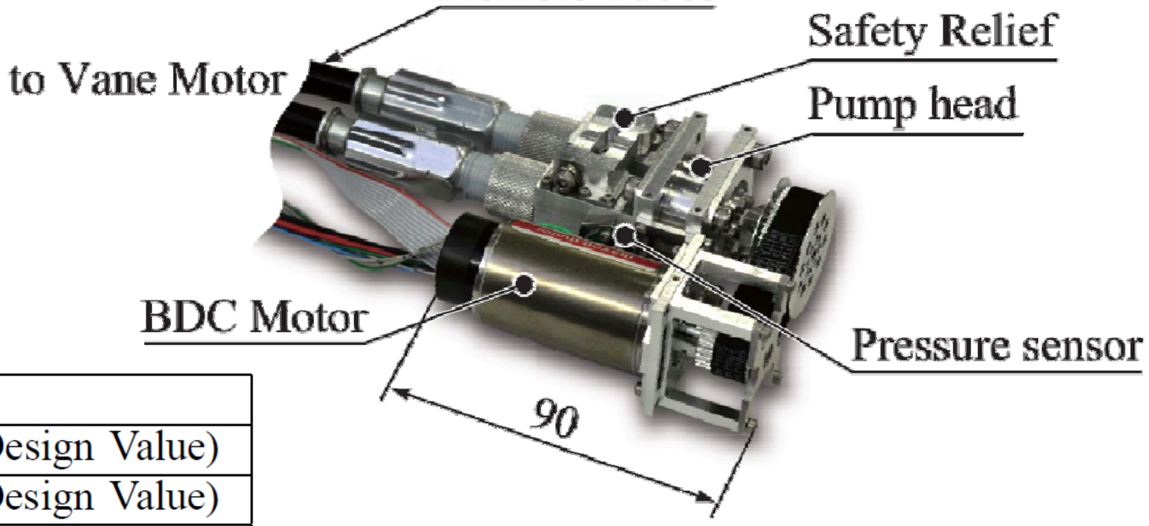
Comparison of Actuation Methods

		Advantage	Drawback	Trade-off
SEA	Low-Pass	Good backdrivability in high frequency	Lack of controllability above resonance frequency	Backdrivability and resonance frequency
SDA	High-Pass	Good controllability in high frequency	Lack of backdrivability in high frequency	Backdrivability and efficiency

Total backdrivability is necessary

Developed Components





Part	Mass
Pump	299.6 (g) (Dry Weight, Design Value)
Motor	541 (g) (Dry Weight, Design Value)
Total	1124 (g) (With Oil, Measured Value)

No Friction Compensation

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IFToMM Corld Congress 2011

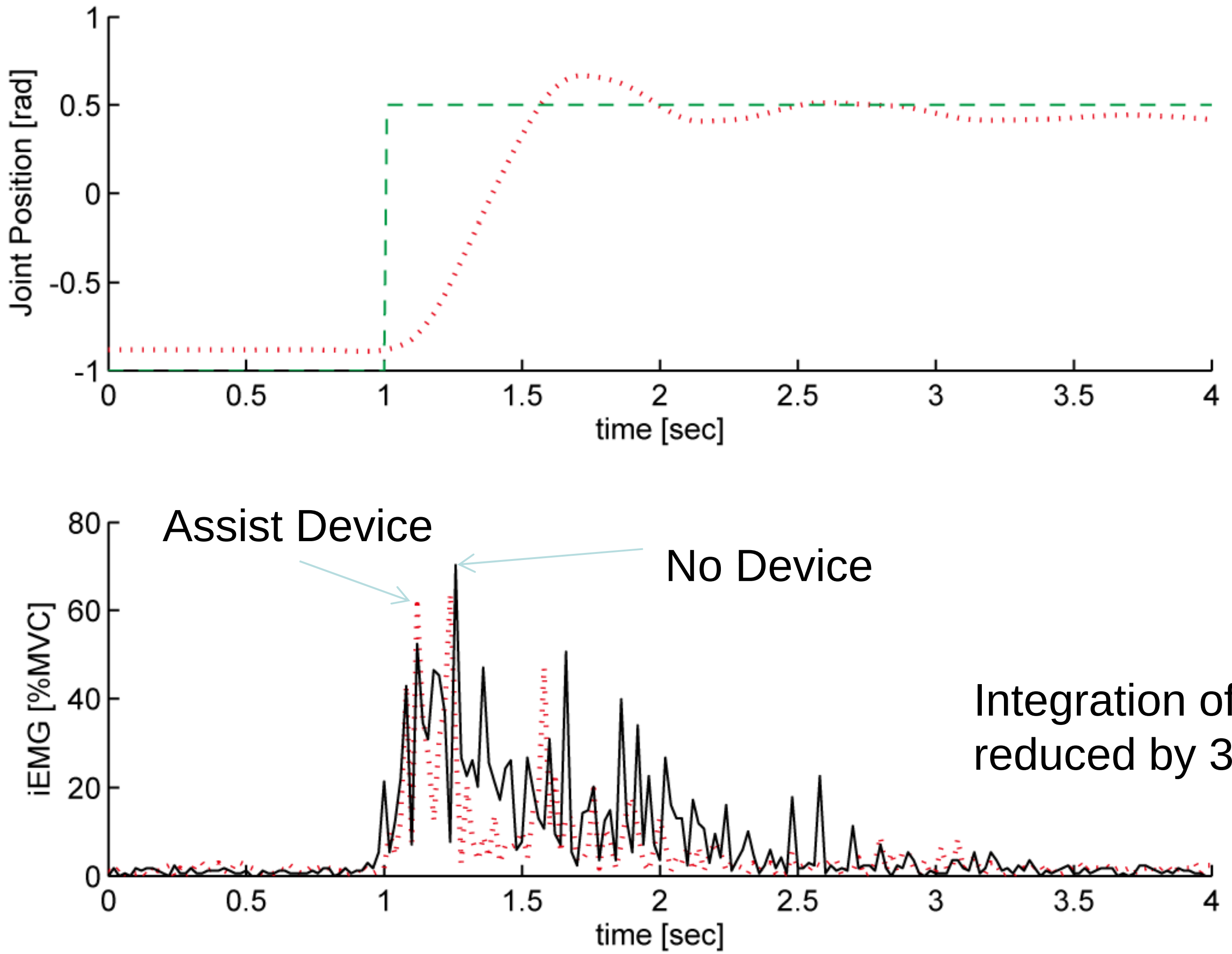
Mechanism and Control of Knee Power Augmenting Device with Backdrivable Electro-Hydrostatic Actuator

Hiroshi Kaminaga, Hirokazu Tanaka, and Yoshihiko Nakamura

Nakamura & Takano Lab.
The University of Tokyo 2011

Power Augmentation Experiment

EMG Comparison in Wearing Device



Assist Device

No Device

Integration of iEMG
reduced by 30%

IEEE Humanoids2011 Poster Presentation

Screw Pump for Electro-Hydrostatic Actuatorthat Enhances Backdrivability

Hiroshi Kaminaga, Hirokazu Tanaka, Kazuki Yasuda, and Yoshihiko Nakamura

Challenges on actuators toward cognitive humanoids

1. More power
2. Back drivability
3. Energy efficiency
4. Accumulation of energy
   (mechanical and/or regeneration/recharging/capacitor)
5. High bandwidth for human-humanoid physical interaction