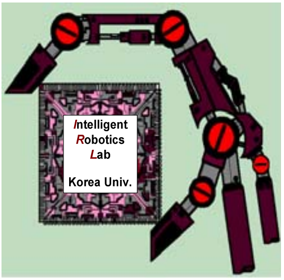
Variable Stiffness Actuation based on Dual Actuators Connected in Series and Parallel



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Various Variable Stiffness Devices at Korea Univ.

Serial-type Dual Actuator Unit

- Serial connection
- Position control
- Stiffness control
- Force estimation
- Collision safety
- Environment estimation

Safety Joint Mechanism

- Passive compliance
- 1 rotational DOF
- Joint type
- pHRI

Parallel-type Dual Actuator Unit

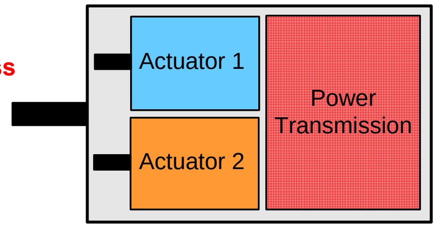
- Parallel connection
- Antagonistic actuation
- Variable stiffness
- Parallel actuation

Safety Link Mechanism

- Passive compliance
- 3 rotational DOFs
- Link type
- pHRI

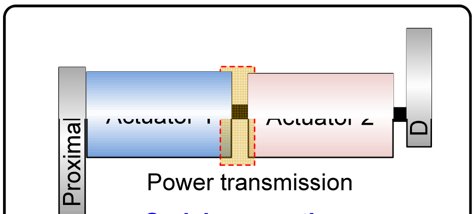
Dual Actuator Unit (DAU)

- **Redundant Actuation**
  - **Simultaneous control of position and stiffness for one DOF**
  - **Improved safety**



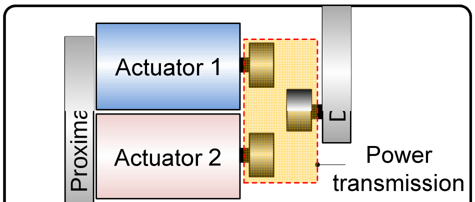
Dual Actuator Unit

- **Two types of DAUs**



Serial connection

Serial-type Dual Actuator Unit (S-DAU)

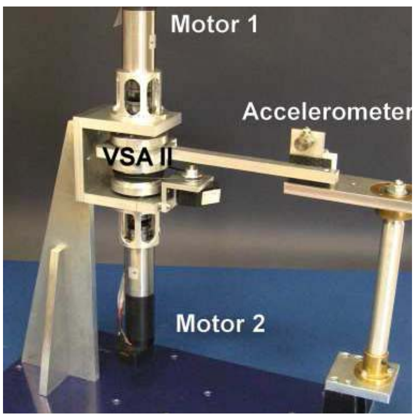


Parallel connection

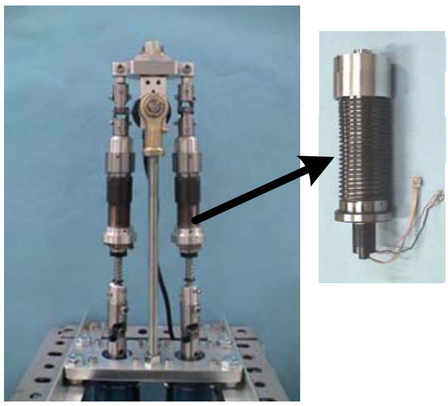
Parallel-type Dual Actuator Unit (P-DAU)

Variable Stiffness Actuators

- **VSA-II (variable stiffness actuation)**
  - **Univ. of Pisa (Bicchi, 2008)**
  - **Torsion spring + 4-bar linkage**

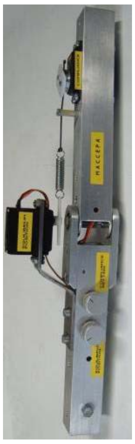


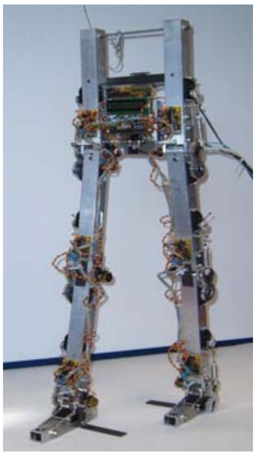
- **ANLES (actuator with nonlinear elastic system)**
  - **Tokai Univ. (Koganezawa, 2006)**
  - **Torsion spring + nonlinear guide**



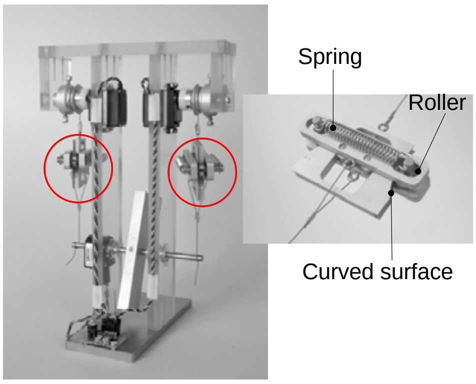
Research Trends: Compliant Actuators

- **MACCEPA** (mechanically adjustable compliance and controllable equilibrium position actuator)
  - Vrije Univ. Brussel (Ham, 2008)

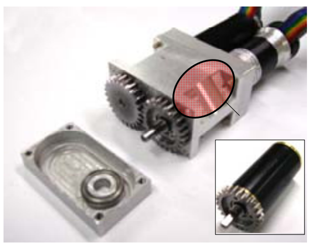




- **Antagonistically actuated joint with quadratic series-elastic actuation**
  - Georgia Tech. (DeWeerth, 2005)
  - Tension spring and curved surface

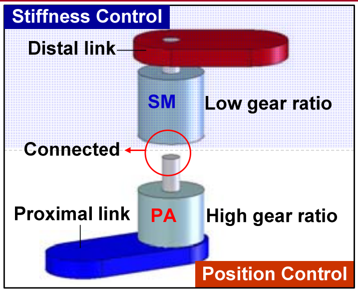


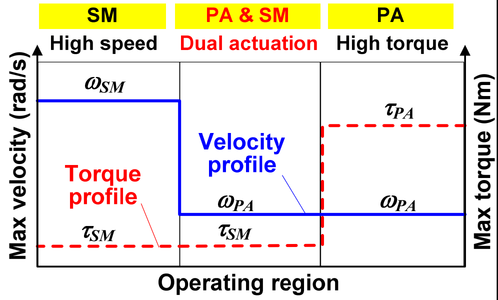
Serial-type Dual Actuator Unit (S-DAU)



S-DAU : Introduction

- **S-DAU**
  - **Connected in series**
  - **Based on planetary gear train**
- **Features**
  - **Positioning actuator (PA) with high gear ratio**
  - **Stiffness modulator (SM) with low gear ratio**
  - **Indep. control of position and stiffness**
  - **Force estimation**
  - **Collision safety**
  - **Stiffness estimation**
  - **Environment estimation**

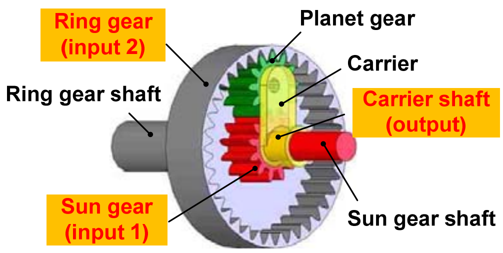




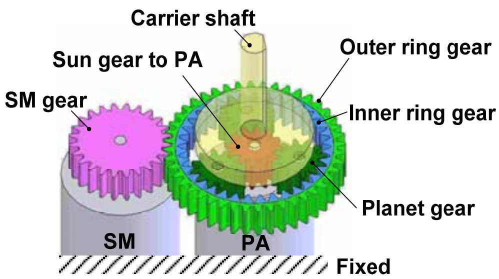
S-DAU : Principle of Operation

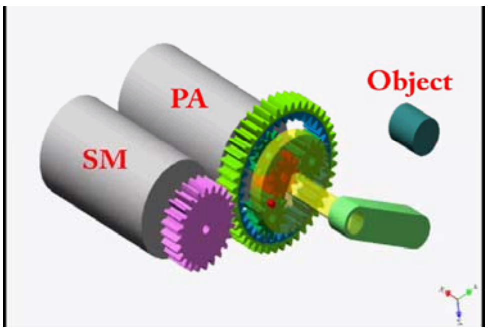
- **Planetary gear train**
  - **Two inputs & One output**

    → Useful for actuator unit with dual inputs



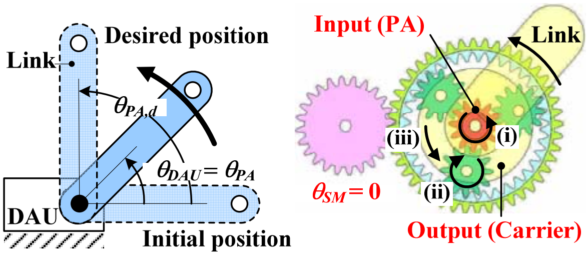
- **S-DAU based on planetary gear train**

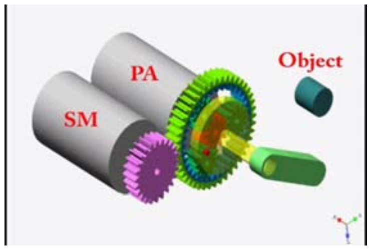




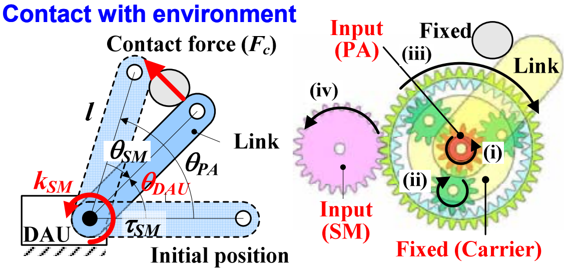
S-DAU : Principle of Operation

- No contact with environment





- Contact with environment



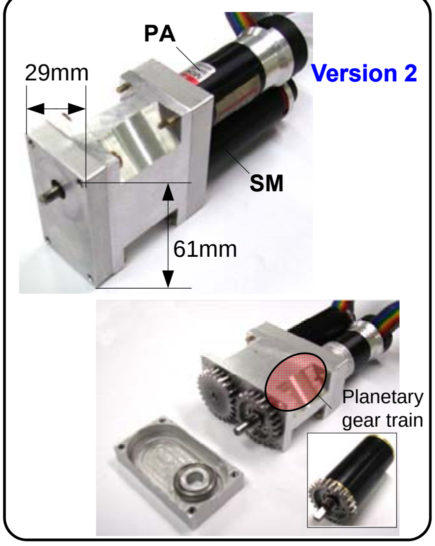
$$\theta_{DAU} = \theta_{PA} + \theta_{SM}$$

$$\begin{cases} \tau_{SM} = k_{SM} \cdot \theta_{SM} \\ \tau_{SM} = K_{T,SM} \cdot i_{SM} \end{cases}$$

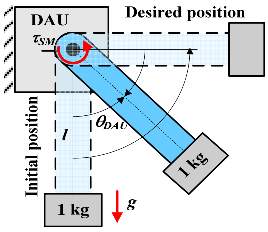
$$\Rightarrow i_{SM} = \frac{k_{SM} \cdot \theta_{SM}}{K_{T,SM}}$$

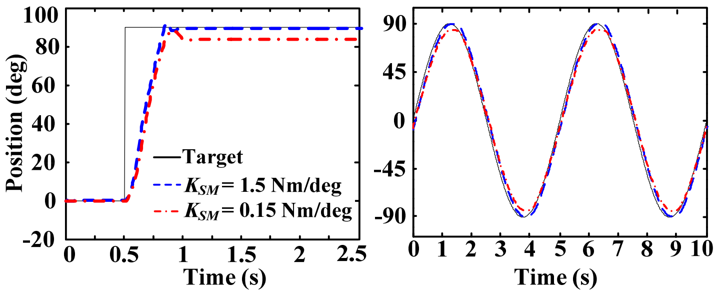
S-DAU : Construction

- Planetary gear train
- Gear ratio
  - 690:1 for PA, 56:1 for SM
- Version 1 : 48x61x110 mm, 500g (including clutch mechanism)
- Version 2 : 26x61x110 mm, 450g

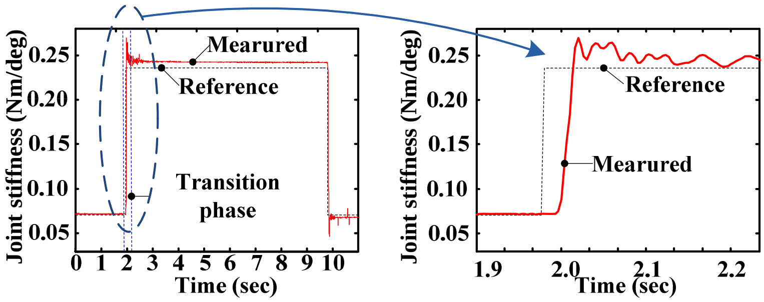


S-DAU : Position Control / Stiffness Control





Response to stiffness change

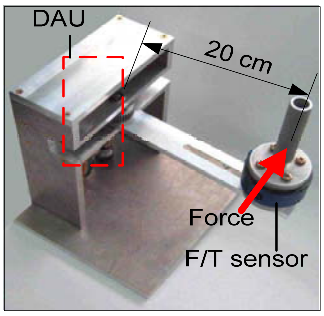


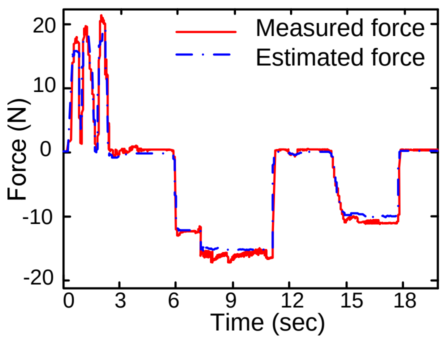
S-DAU : Force Estimation

- **Force estimation**
  - **No need for an expensive F/T sensor for force control**

$$\tau_{SM} = k_{SM} \cdot \theta_{SM} \quad \Rightarrow \quad \tau_{SM} = J^T \cdot F$$

  - k_{SM} **: user specified**
  - θ_{SM} **: measured by the SM encoder**





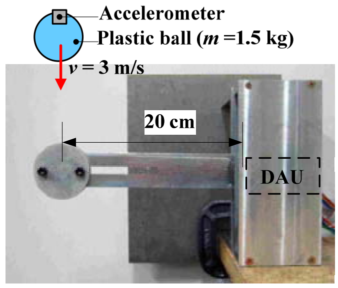
S-DAU : Collision Safety

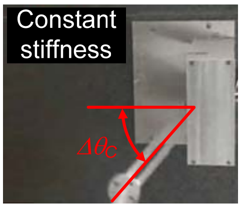
- **Joint Stiffness :** $k_{SM} = k_{SM}^{o} - \beta_{vel} \cdot \Delta\omega$
  - k_{SM}^{o} : initial stiffness, $\Delta\omega = \omega_{SM} - \omega_{o}$
  - **Example**

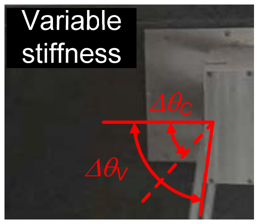
    ω_{SM}= *270* deg/s, ω_{o} = 170 deg/s,

    k_{SM}^{o} = 1.5 Nm/deg, β_{vel} = 0.01,

    → k_{SM} = 0.5 Nm/deg just after collision

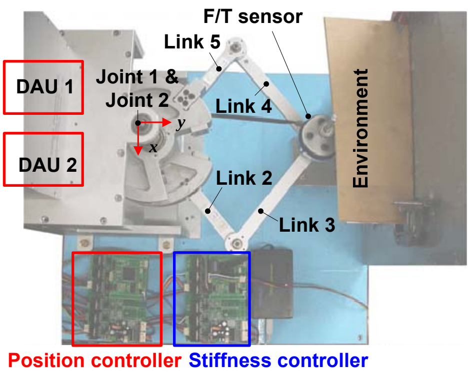


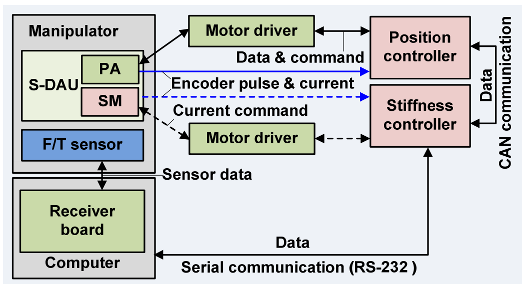




S-DAU : Parallel Manipulator with Two S-DAUs

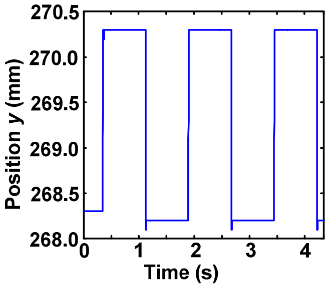
- **Experimental Setup**
  - 5-linkage parallel manipulator with two S-DAUs.
  - Independent position and stiffness controllers based on DSP 2812.
  - Verifies S-DAU's force estimation ability using a F/T sensor.



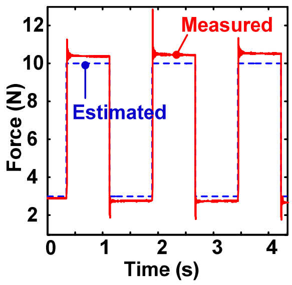


S-DAU : Stiffness Estimation

- **Stiffness estimation for hard material**
  - **Applied force : 3N → 10N**
  - **Stiffness of environment K_e :**
    - **- 3.5kN/m (estimated), 3.75kN/m(measured)**
  - **Stiffness of manipulator K_{SM}: about 100N/m**



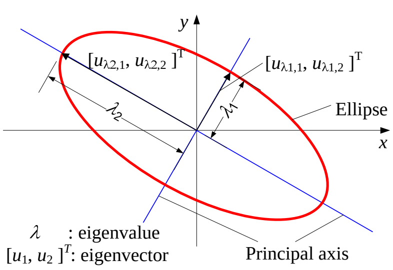
Position information

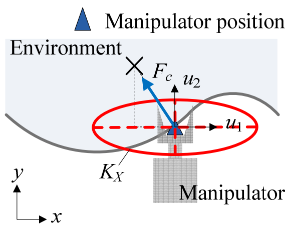


Estimated stiffness

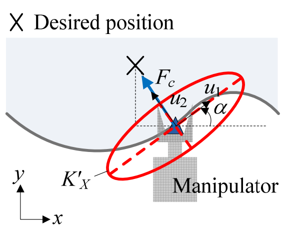
S-DAU : Stiffness Adaptation

- **Stiffness**
  - **Stiffness matrix → stiffness ellipse in Cartesian space**
  - **Low stiffness in normal direction → Good control of contact force**
  - **High stiffness in tangential direction → Good performance on trajectory tracking**
  - **Stiffness ellipse adaptable to surface normal using the estimated force**





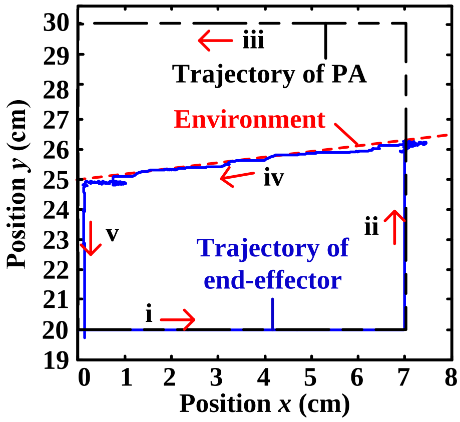
Fixed stiffness ellipse



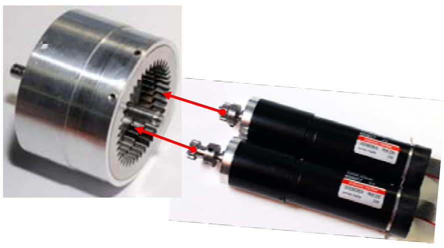
Adaptable stiffness ellipse

S-DAU : Surface Estimation

- Surface estimation



Parallel-type Dual Actuator Unit (P-DAU)

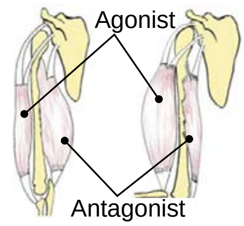


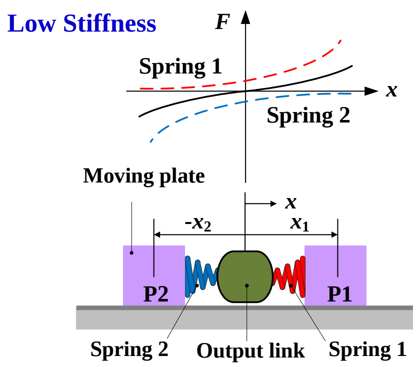
P-DAU : Introduction

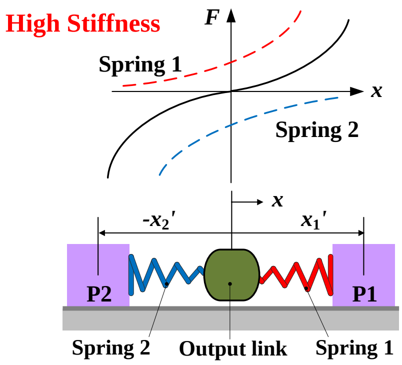
- **P-DAU**
  - **Connected in parallel**
  - **Antagonistic actuation**
- **Features**
  - **Linear spring + Cam-follower**
    - **→ Nonlinear stiffness characteristics**
  - **Compact design**
  - **Parallel actuation available**
    - **→ Combined torques from dual actuators**

P-DAU : Principle of Operation

- **Antagonistic actuation**
  - **Basic principle of human motion**
  - **Two muscles for control of a single joint.**
  - **Muscles modeled as nonlinear springs .**

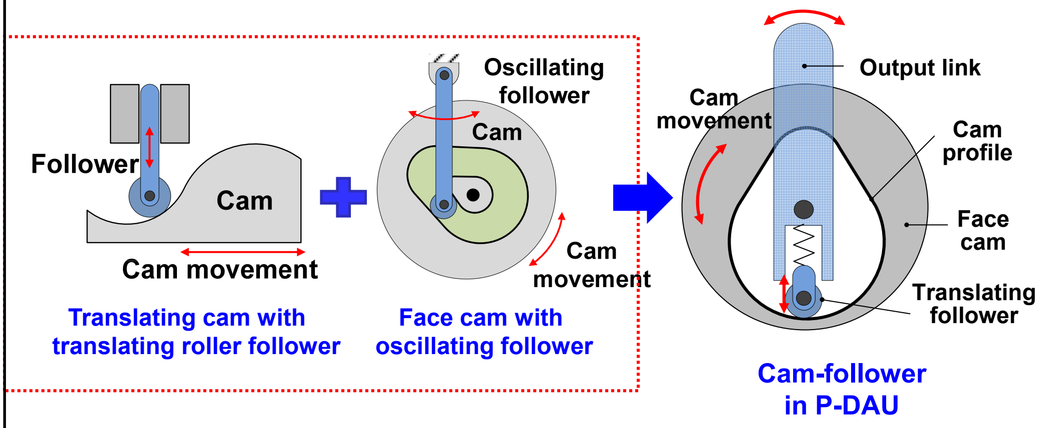






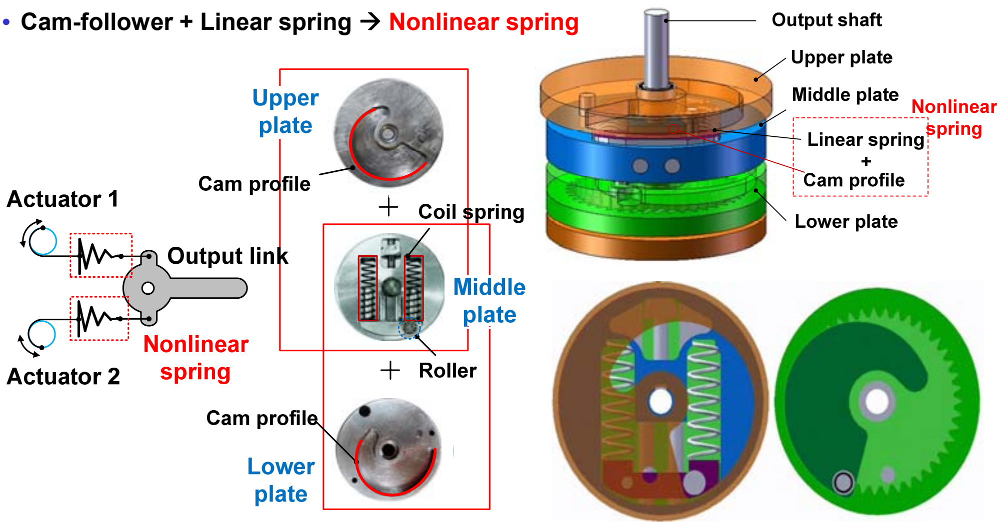
P-DAU : Principle of Operation

- **Cam-Follower Mechanism**
  - **Compact design.**
  - **Cam profile → Various nonlinear characteristics.**



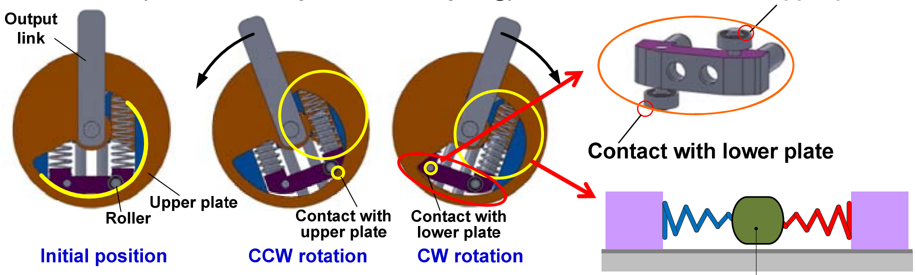
P-DAU : Principle of Operation

- **Variable Stiffness mechanism of P-DAU**
  - **Antagonistic actuation**
  - **Cam-follower + Linear spring → Nonlinear spring**

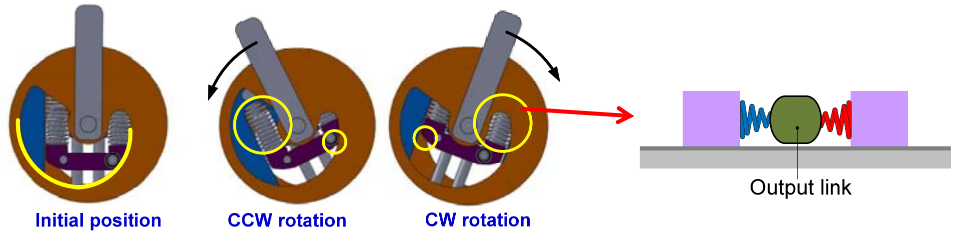


P-DAU : Variable Stiffness Mechanism

- **Low Stiffness** (→ Small compression of spring)

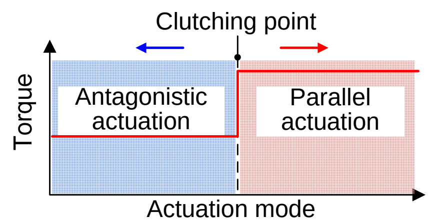


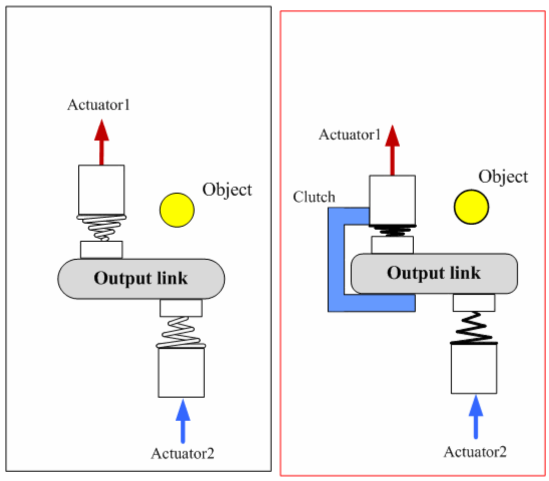
- **High Stiffness** (→ Large compression of spring)



P-DAU : Parallel Actuation

- **Parallel actuation**
  - **Antagonistic actuation: Only a single actuator can apply a force to an object.**
  - **Parallel actuation: Both actuators can apply forces to an object.**
    - **→ Combined torque from dual actuators**
    - **→ No variable stiffness**



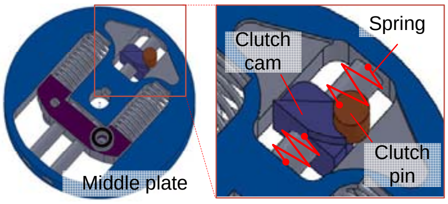


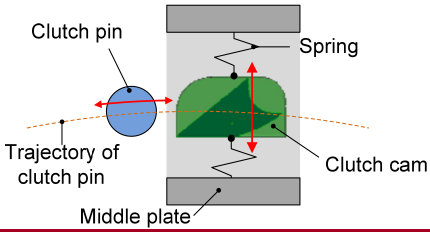
Antagonistic actuation

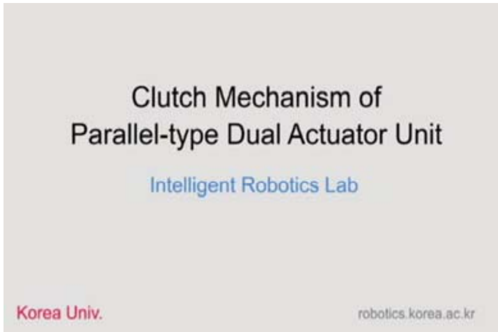
Parallel actuation with clutch mechanism

P-DAU : Parallel Actuation

- **Clutch mechanism**
  - **Based on cam-profile.**
  - **Operated by the difference in position between upper and lower plates.**

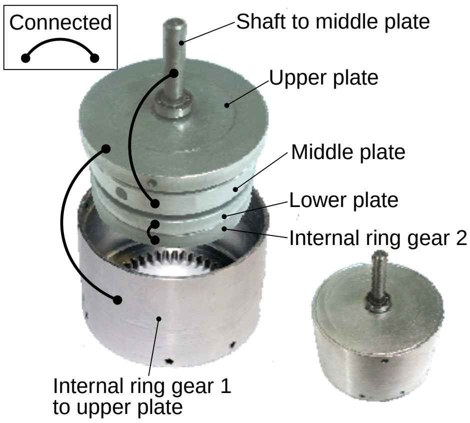


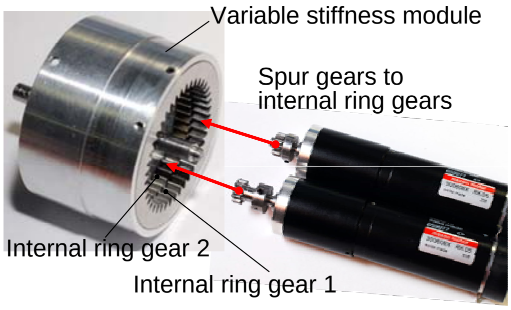




P-DAU : Construction

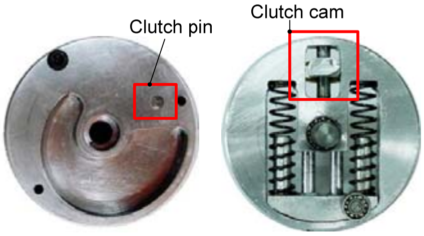
- **Actuation Mechanism of P-DAU**
  - **Compact design → power transmission by two Internal ring gears**



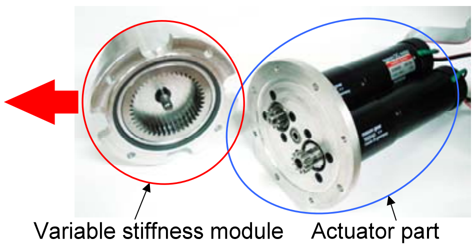


P-DAU : Construction

- ϕ70x62 mm, 470g (without motors)
- Maximum payload: 5Nm
- Variable stiffness range: 0.01 ~ 0.6 Nm/deg
- Response time : < 1sec
  (from min. stiffness to max. stiffness)

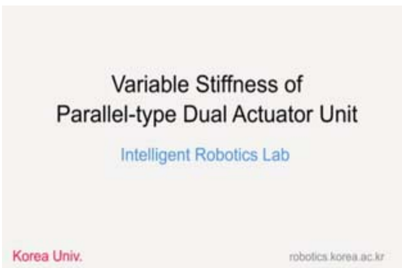


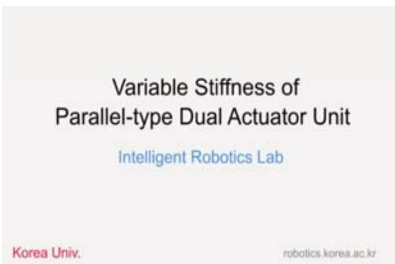
Upper/Lower plate **Ver. 1**



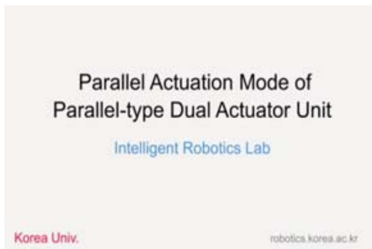
P-DAU : Performance

- **Antagonistic Actuation Mode**

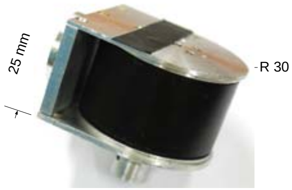


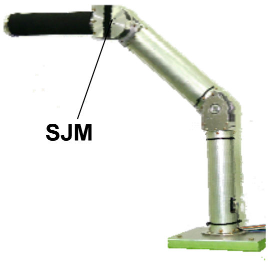


- **Parallel Actuation Mode**



Safe Joint Mechanism (SJM)

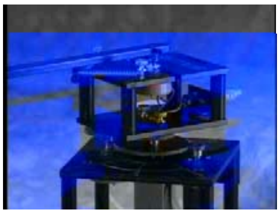




SJM : Introduction

- Safe robot arm (Compliant robot arm)
  - Active compliance
    - Collision detection by sensors
      → Control of actuators
    - Slow response, noise, malfunction

  - Passive Compliance
    - Spring, flexible link/joint, soft covering
      → Absorbing collision force
    - Fast response, high reliability
      but positioning inaccuracy.

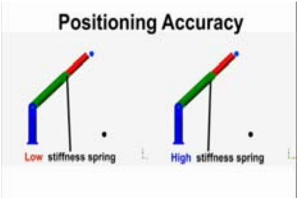


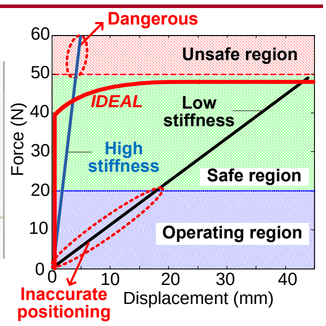
Flexible joint (Quanser)

Rovie, ATR

SJM : Principle of Operation

- Safety vs Performance
  - Tradeoff
  - Low stiffness for safety
  - High stiffness for performance

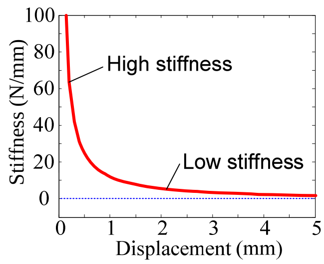


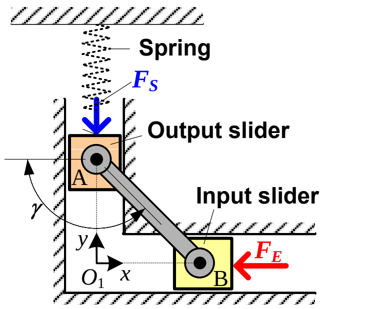


- Our approach
  - Nonlinear stiffness characteristics
    → Only by passive mechanical elements
  - Normal operation
    → Stiff arm for accurate positioning
  - Collision situation (Large impact)
    → Soft arm for shock-absorbing

SJM : Principle of Operation

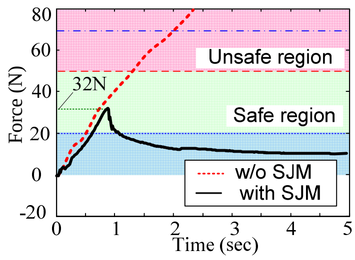
- Nonlinear spring system
  - 4-bar linkage + Pre-compressed spring
  - Transmission angle of 4-bar linkage
    → Low spring force for static equilibrium
  - Threshold force: Transmitted force ≥ Spring force

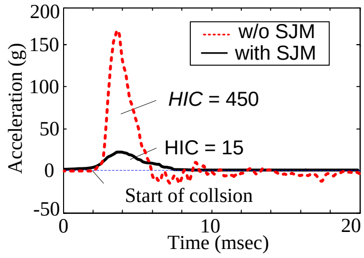




γ : transmission angle
F_E : External force F_S : Spring force

SJM : Performance





SJM : Current Status

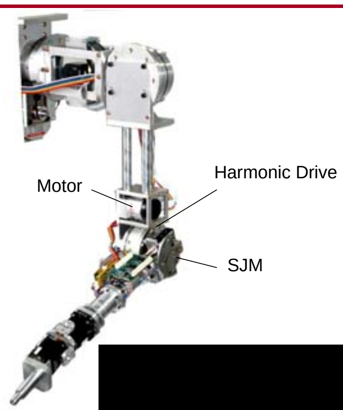
- **Safe manipulator**
  - **6 DOF manipulator with SJM**
  - **SJM installed at the elbow joint.**

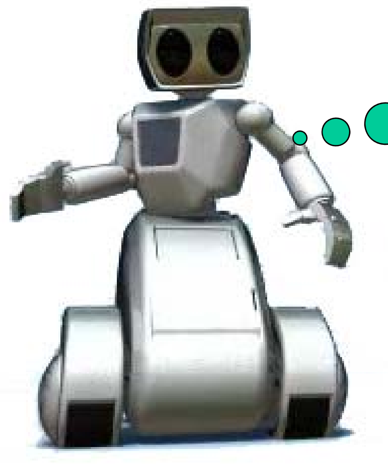
3rd version

- **Size : Ø65*25mm**
- **Weight : 125g**
- **Torque : 8.5 Nm**
- **Range : ± 25°**
- **HIC : below 100**

2nd version

- **Size : Ø75*35mm**
- **Weight : 180g**
- **Torque : 10 Nm**
- **Range : ± 23°**
- **HIC : below 100**





Thank you !!

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