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

**Parallel-type Dual Actuator Unit**
- Parallel connection
- Antagonistic actuation
- Variable stiffness
- Parallel actuation

**Safety Joint Mechanism**
- Passive compliance
- 1 rotational DOF
- Joint type
- pHRI

**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

- Two types of DAUs

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

\[ \theta_{DAU} = \theta_{PA} + \theta_{SM} \]

- Contact with environment

\[ \tau_{SM} = k_{SM} \cdot \theta_{SM} \]
\[ \tau_{SM} = K_{T,SM} \cdot i_{SM} \]
\[ i_{SM} = \frac{k_{SM} \cdot \theta_{SM}}{K_{T,SM}} \]

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**

![Diagram of S-DAU](image)

Response to stiffness change

**Joint stiffness (Nm/deg)**

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Measured Force</th>
<th>Estimated Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>1</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>5</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
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<td>0.35</td>
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<tr>
<td>7</td>
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<tr>
<td>8</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>9</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>10</td>
<td>0.55</td>
<td>0.55</td>
</tr>
</tbody>
</table>

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**S-DAU : Force Estimation**

- **Force estimation**
  - No need for an expensive F/T sensor for force control
  
    \[ \tau_{SM} = k_{SM} \cdot \theta_{SM} \quad \Rightarrow \quad \tau_{SM} = F^T \cdot F \]
  
  - \( k_{SM} \) : user specified
  - \( \theta_{SM} \) : measured by the SM encoder

![Diagram of S-DAU with force estimation](image)

**Measured force**

![Graph of force over time](image)

**Estimated force**

![Graph of force over time](image)

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S-DAU: Collision Safety

- **Joint Stiffness**: \( k_{SM} = k_{SM}^0 - \beta_{vel} \cdot \Delta \omega \)
  - \( k_{SM}^0 \): initial stiffness, \( \Delta \omega = \omega_{SM} - \omega_o \)
  - Example
    - \( \omega_{SM} = 270 \text{ deg/s} \), \( \omega_o = 170 \text{ deg/s} \),
    - \( k_{SM}^0 = 1.5 \text{ Nm/deg} \), \( \beta_{vel} = 0.01 \),
    - \( k_{SM} = 0.5 \text{ Nm/deg} \) 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

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

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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.

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[Diagram showing the principle of operation with low and high stiffness settings]
Cam-Follower Mechanism
- Compact design.
- Cam profile → Various nonlinear characteristics.

Cam-follower in P-DAU

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)
  - Initial position
  - CCW rotation
  - CW rotation
  - Output link
  - Contact with upper plate
  - Contact with lower plate

- **High Stiffness** (→ Large compression of spring)
  - Initial position
  - CCW rotation
  - CW rotation
  - Output link
  - Contact with upper plate
  - Contact with lower plate

**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

- **Actuation mode**
  - **Antagonistic actuation**
  - **Parallel actuation**
  - Clutching point
  - Torque
  - Antagonistic actuation
  - Parallel actuation
  - Actuation mode

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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

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Clutch Mechanism of Parallel-type Dual Actuator Unit
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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)

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.
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

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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
SJM : Performance

![Graph showing force and acceleration over time for SJM and w/o SJM with and without collision]

SJM : Current Status

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

<table>
<thead>
<tr>
<th>3rd version</th>
<th>2nd version</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Image of 3rd version SJM" /></td>
<td><img src="image2" alt="Image of 2nd version SJM" /></td>
</tr>
</tbody>
</table>

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

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

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