Development of Electric Cart for Improving Walking Ability

---Application of Control Theory to Assistive Technology---

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- Measures for Aging Society from Japanese Government
- Configuration of Electric Cart Control System
- Design of Cart Control System
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  - Step 2: Design of Controller for a Selected Load
  - Step 3: Automatic Selection of a Load Based on Driver’s Physical Condition
- Experimental Results
Aging in Japan

Percentage of old people (≥ 65 yrs old) in the population

1950 55 60 65 70 75 80 85 90 95 00 05 10 14 15 20 25 30 35 40

~ 21% super-aged society
2015: 26.7%
14 ~ 21% aged society
7 ~ 14% aging society


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Demography of Japan

From: Statistics Bureau, Ministry of Internal Affairs and Communications, Japan

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1/2.5: $\geq 65$ yrs old
1/4: $\geq 75$ yrs old
Population $\sim 87$ million
Aging rate $\sim 40\%$
Measures for Aging Society from Japanese Government

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Priority Research Areas

Ministry of Economy, Trade, and Industry and Ministry of Health, Labour, and Welfare

Priority areas for robotic technology in nursing care:

- Lifting aids
- Mobility aids
- Toilets
- Monitoring systems for people with senile dementia
- Bathing

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Motivation

Electric carts for the elderly

- Designed solely as a means of transportation
- No consideration was given to an elderly person's need for physical exercise
Muscular Degeneration Due to Aging

Volume of brachial-flexor muscles
- Men: 200 ~ 300 cm³  Women: 150 ~ 200 cm³

Upper limbs are litter affected by aging.

Volume of femoral-flexor muscles
- Maximum during 20s ~ 30s:
  - Men: 1700 cm³  Women: 1200 cm³
- In 70s:
  - 60% of the maximum

Lower limbs become markedly weaker in later life!
Walking Muscles

Weaker in later life:
Loin, front thigh, shin, calf.

Loin + Front thigh: too weak
Leg cannot be lifted

Shin: too weak
Toes cannot be raised

Calf: too weak
Heel cannot be raised
Prevention Measures

Walking muscles need exercise.

Cycling is the ideal exercise to work the muscles.

Pedal down: front thigh, calf, and hamstring
Pedal up: loin, front thigh, and shin

Mount two foot pedals on an electric cart to exercise the walking muscles
New Electrical Cart

Everyday Type-S (Araco Corp., Japan)

Two pedals.
- The load generated by the pedal motor is responsive to the road conditions.
- Electrical connection between pedals and drive wheels.
Pedal Unit

- Pedal load:
  Responsive to road conditions:
  More realistic driving experience

- Installation:
  Optimal pedaling region

Ergonomic mounting of seat and pedal unit
A Photo of New Electrical Cart

Everyday Type-S (Araco Corp., Japan)
Interface Board

Controller (Computer) → Parallel port

Voltage to pedal motor

Voltage to cart motor

Rotational angle of pedal motor

Rotational angle of cart motor

Motor driver

D/A Converter (8 bits)

D/A Converter (8 bits)

Counter (8 bits)

Counter (8 bits)

From pedal optical encoder

To pedal motor

From cart optical encoder

To cart motor

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Configuration of Bilateral Master-Slave Cart System (1)

First-order plant is easy for humans to operate.

Controlled output: Speed

Reference input for cart: Speed of pedal motor

Speed of cart motor motor tracks speed of pedal motor
Configuration of Bilateral Master-Slave Cart System (2)
Modeling of Pedal and Cart

Pedal system:
\[
\frac{dv_m(t)}{dt} = A_m v_m(t) + B_m u_m(t) + B_f f(t),
\]
\[
A_m = \frac{c_m}{J_m}, \quad B_m = \frac{k_m}{J_m}, \quad B_f = \frac{1}{J_m}.
\]

Cart system:
(Wt. of driver: 45 ~ 100 kg)
\[
\frac{dv_s(t)}{dt} = A_s v_s(t) + B_s u_s(t),
\]
\[
A_s(t) := A_s + \Phi \Gamma \% A, \quad B_s := B_s + \Phi \Gamma \% B, \quad \Gamma^2 \leq 1.
\]
Controller Design

Step 1
Design of controllers for three different loads
Determination of Max. Pedal Load (1)

Rating of perceived exertion: \( r_{PE} = 20\% \)  (Level of exertion for walking)

Maximum heart rate: \( r_{Hm} = 220 - \text{age} \)

Target heart rate (Karvonen formula):
\[
r_{Ht} = r_{Hr} + r_{PE} (r_{Hm} - r_{Hr})
\]

\( r_{Hr} \): Heart rate at rest
Determination of Max. Pedal Load (2)

Pushing force test:
Adjust the load of the ergometer so that the heart rate stabilizes at the target heart rate.

Based on the test results and considering aging effect:
Max. pedal load: \[ f_{\text{max}} = 40 \text{ N} \]
Introduction of an Impedance Model

Impedance Model:

Describes feeling of pushing pedals.

\[
\frac{dv_p(t)}{dt} = A_p v_p(t) + B_p f(t)
\]

<table>
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<tr>
<th>Mode</th>
<th>(A_p)</th>
<th>(B_p)</th>
</tr>
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<tbody>
<tr>
<td>Strenuous</td>
<td>–1.49</td>
<td>2.00</td>
</tr>
<tr>
<td>Neutral</td>
<td>–1.49</td>
<td>3.49</td>
</tr>
<tr>
<td>Assisted</td>
<td>–1.49</td>
<td>3.90</td>
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Formulation of Control Problem

Find a controller $K(s)$ such that

- the cart control system is internally stable.
- $\|G_{zw}\|_\infty < 1$.

$f_w(t)$: Relaxes the solvable condition

$$w(t) = \begin{bmatrix} f(t) & f_{\Gamma}(t) & f_w(t) \end{bmatrix}^T$$

$$z(t) = \begin{bmatrix} z_m(t) & z_{ve}(t) & z_{\Gamma}(t) & z_{as}(t) & z_{us}(t) & z_{um}(t) \end{bmatrix}^T$$
Weighting Functions

$W_{em}(s)$: To suppress the tracking error between $v_p(t)$ and $v_m(t)$.

$W_e(s)$: To suppress the tracking error between $v_m(t)$ and $v_s(t)$.

$W_{um}(s)$: To suppress the control voltage $u_m(t)$.

$W_{us}(s)$: To suppress the control voltage $u_s(t)$.

$W_s(s)$: Riding comfort.
Experimental Conditions

**Impedance models:**
- Strenuous Mode
- Neutral Mode
- Assisted Mode

**Road conditions:**
- flat road
- 5° uphill slope
- 5° downhill slope

**Weight of driver:**
- 47 ~ 70 kg
Exp. Results 1: Flat Road

Strenuous Mode

\[ u_m \ \text{avg}(15–25) = -0.462 \ \text{V} \]

Neutral Mode

\[ u_m \ \text{avg}(15–25) = -0.047 \ \text{V} \]

Assisted Mode

\[ u_m \ \text{avg}(15–25) = 0.377 \ \text{V} \]

Weight of driver: 63 kg

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Exp. Results 2: Uphill Slope

\[ u_m \; \text{avg}(15-25) = -0.993 \; \text{V} \]

\[ u_m \; \text{avg}(15-25) = -0.088 \; \text{V} \]

\[ u_m \; \text{avg}(15-25) = 0.866 \; \text{V} \]

Weight of driver: 63 kg
Exp. Results 3: Downhill Slope

**Weight of driver:** 63 kg

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Controller Design

Step 2
Design of controller for a selected load
Load Adjusting Function

Neutral (Mode N)

Strenuous (Mode S)

Assisted (Mode A)
Gain-Scheduling Control System for Any Level of Load/Assistance (1)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Controller</th>
<th>Control input</th>
</tr>
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<tbody>
<tr>
<td>Strenuous</td>
<td>$C_S$</td>
<td>$u_S$</td>
</tr>
<tr>
<td>Neutral</td>
<td>$C_N$</td>
<td>$u_N$</td>
</tr>
<tr>
<td>Assisted</td>
<td>$C_A$</td>
<td>$u_A$</td>
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Designed controllers: $C_S$, $C_N$, $C_A$

Dynamic parallel distributed compensation

Automatic generation of controller for any level of load/assistance
Gain-Scheduling Control System for Any Level of Load/Assistance (2)

Control input:

\[ u(t) = \lambda_S u_S(t) + \lambda_N u_N(t) + \lambda_A u_A(t) \]

\( \lambda_S, \lambda_N, \lambda_A \) : Coefficients

\( \lambda_S + \lambda_N + \lambda_A = 1 \)

The above control law guarantees the stability of the closed-loop cart control system if there exists a common symmetric positive definite matrix \( P \) such that the following hold:

\[ P \tilde{A}_S(\Gamma) + \tilde{A}_S^T(\Gamma)P < 0, \]

\[ P \tilde{A}_N(\Gamma) + \tilde{A}_N^T(\Gamma)P < 0, \]

\[ P \tilde{A}_A(\Gamma) + \tilde{A}_A^T(\Gamma)P < 0. \]

\( \tilde{A}_i(\Gamma) \) \( (i = S, N, A) \) : System matrix of the closed-loop system.
Experimental Results (Flat Road)

Average input voltage of pedal motor

- Applied voltage (V)
- Strenuous
- Neutral
- Assisted

Average pushing force on pedals

- Pushing force (N)
- Load
- Assisted

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Controller Design

Step 3

Automatic selection of a load
Automatic Selection of Pedal Load

Pedal load

Mode

Natural

Strenuous

0% 20% 40% 70%

Rating of perceived exertion

$R_{PE}$

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Exp. Results: $B_p$ vs. $r_{PE}$

- **Natural**
  - $B_p$
  - $r_{PE}$

- **Strenuous**
  - $B_p$
  - $r_{PE}$

- **Subject 1 (21 years old)**
- **Subject 2 (83 years old)**

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Exp. Results: Avg. $u_m$ vs. $r_{PE}$, Avg. $f$ vs. $r_{PE}$ (Flat Road)
Exp. Results: Steady-state speed for $r_{PE} = 20\%$ (Flat Road)
Summary

New Three-Wheeled Electric Cart

Target: The elderly and people undergoing rehabilitation

Features: Vehicle + Provides physical exercise

Pedal unit: Ergonomic design & mounting

Load selection: 3 loads/Automatic selection

Controller design: $H_\infty$ control theory + Dynamic parallel distributed compensation

Exp. results: The system configuration and the controller are useful for providing an appropriate level of physical exercise.
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Thank you