Development of Electric Cart for Improving Walking Ability

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

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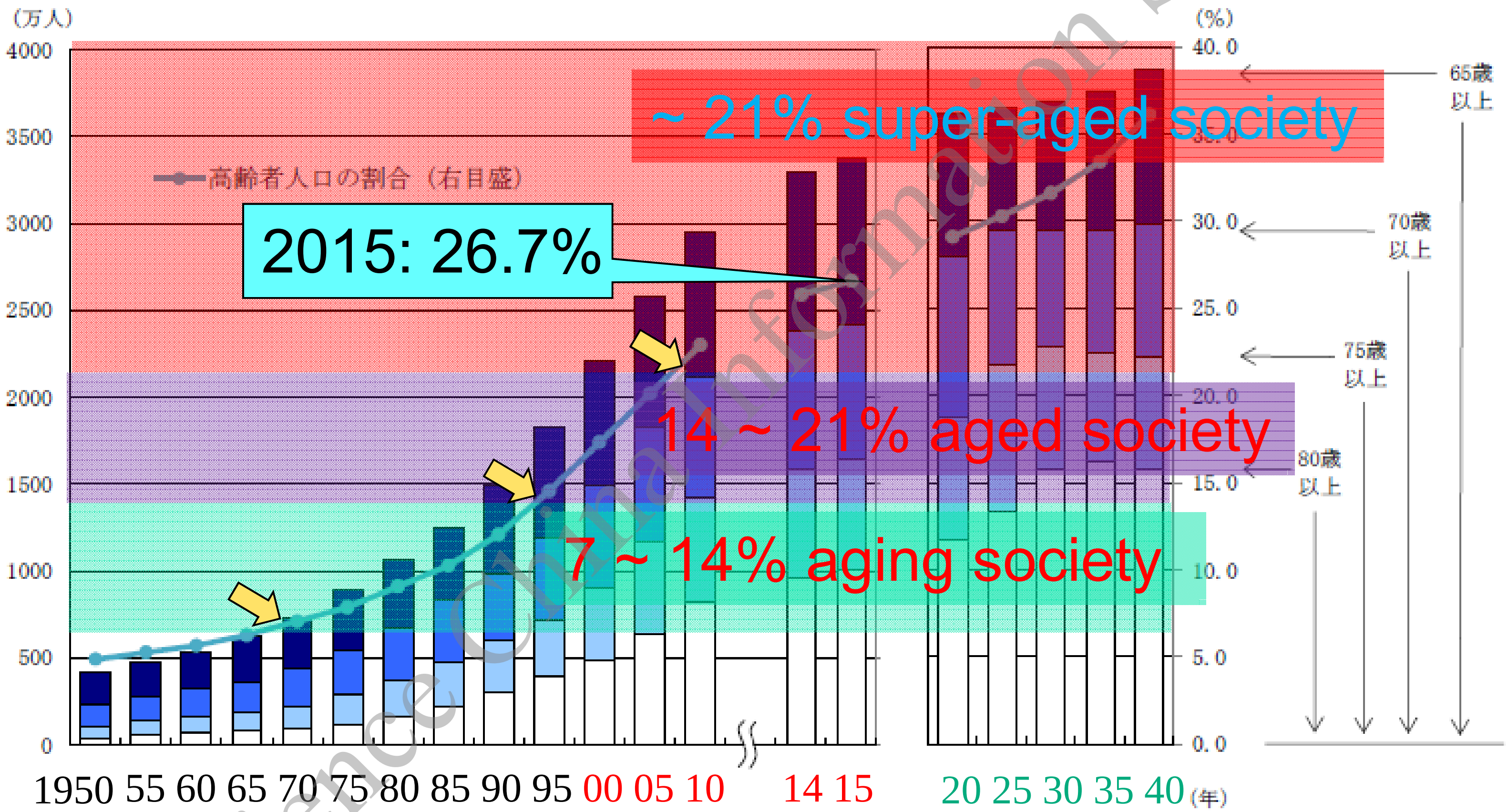
Outline

- Background
- Measures for Aging Society from Japanese Government
- Configuration of Electric Cart Control System
- Design of Cart Control System
  - Step 1: Design of Controllers for Three Different Loads
  - Step 2: Design of Controller for a Selected Load
  - Step 3: Automatic Selection of a Load Based on Driver’s Physical Condition
- Experimental Results

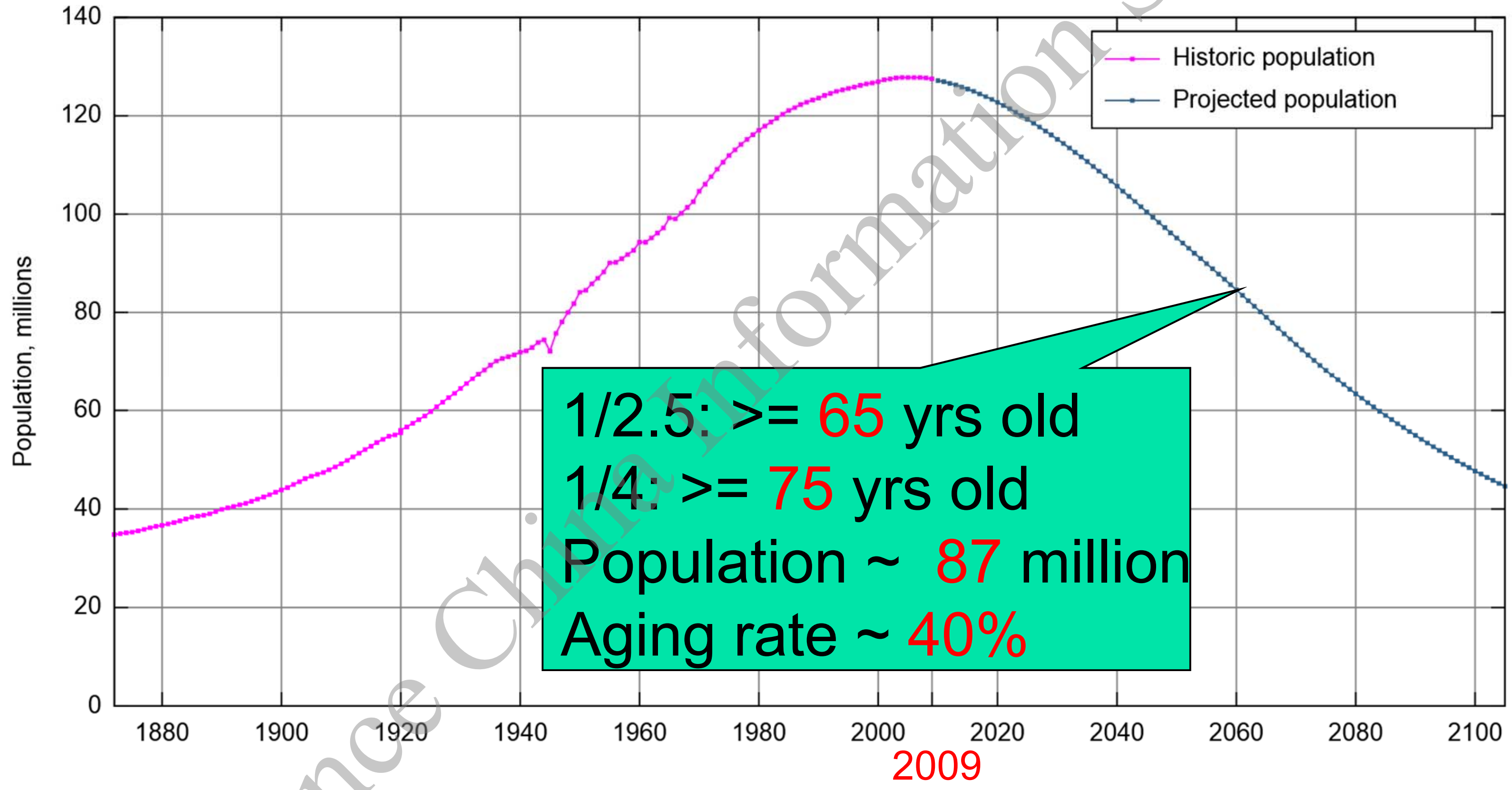
Aging in Japan

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



(Annual Report on the Aging Society, 2017, Cabinet Office)

Demography of Japan



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

Measures for Aging Society from Japanese Government

技術分野別

技術・事業分野	サブカテゴリ	
■エネルギー・環境技術		
・エネルギー	太陽光	風力・海洋
	バイオマス	熱利用
	燃料電池・水素	省エネルギー
	スマートコミュニティ	蓄電池
・環境	3R・水循環	フロン対策
	環境化学	クリーンコール
■産業技術		
・機械システム	ロボット・AI	新製造技術
	福祉用具	
・電子・情報通信	電子デバイス	家電(ディスプレイ、有機トランジスタ、照明)
	ネットワーク／コンピューティング	
・材料・ナノテクノロジー	材料・部材	希少金属
・バイオテクノロジー	バイオシステム	医療システム

Robot & AI

Assistive devices

Medical systems

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

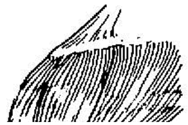
Motivation

- 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 cm^3 Women: 150 ~ 200 cm^3

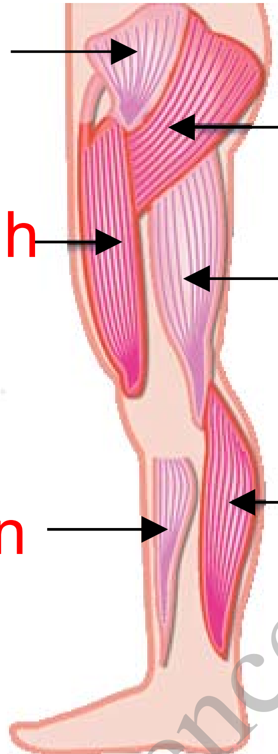


Upper limbs are litter affected by aging.

- Volume of femoral-flexor muscles
  - Maximum during 20s ~ 30s:
    - Men: 1700 cm^3 Women: 1200 cm^3
  - In 70s:
    - 60% of the maximum

Lower limbs become markedly weaker in later life!

Walking Muscles



Weaker in later life:

Lion, 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:

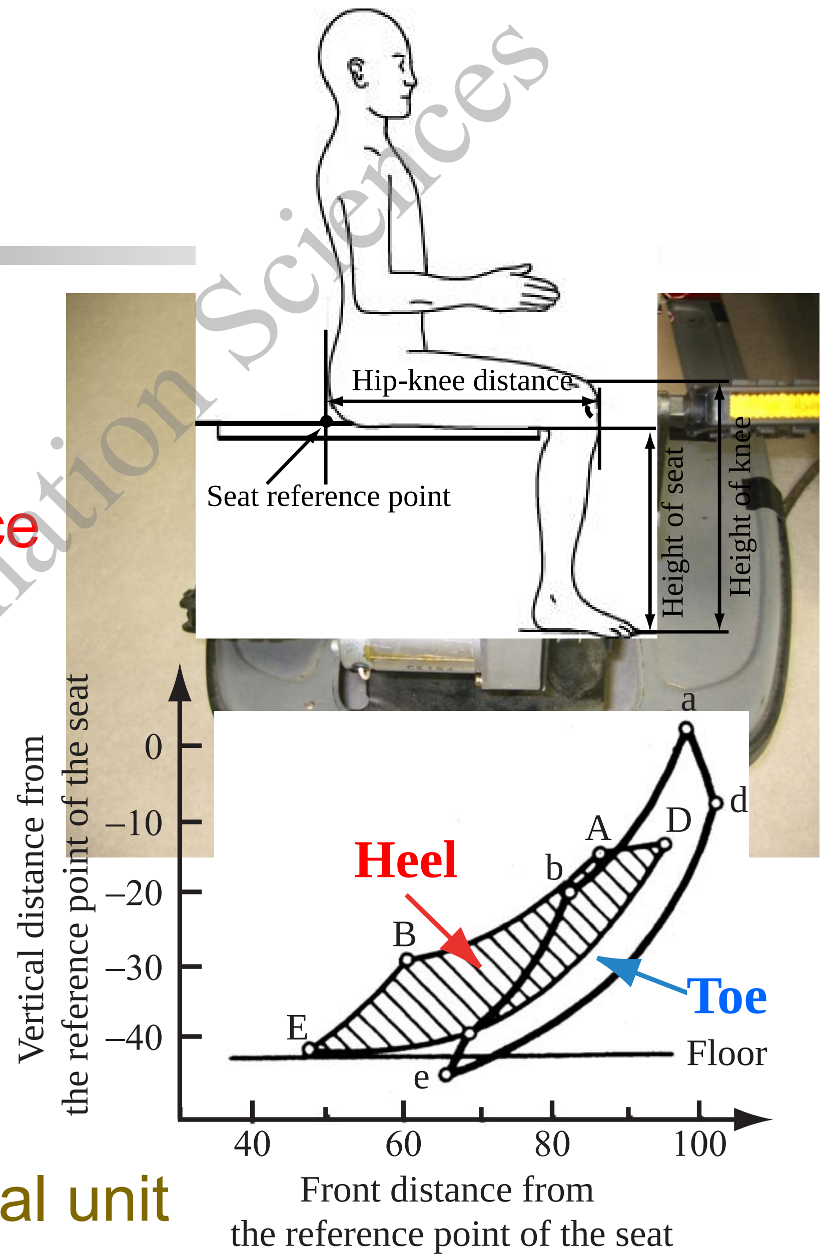
  Responsive to road conditions:

  More realistic driving experience

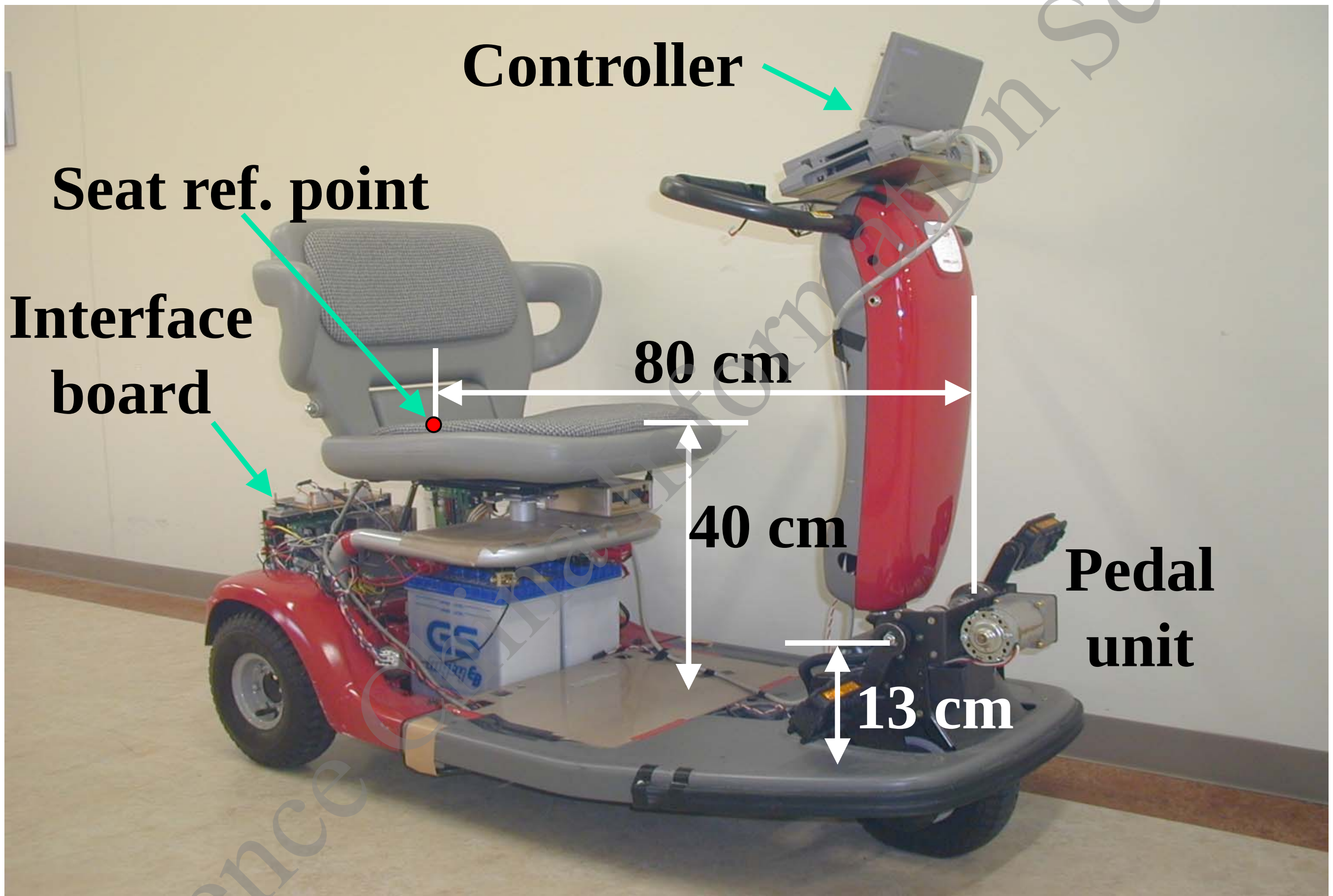
- Installation:

  Optimal pedaling region

Ergonomic mounting of seat and pedal unit

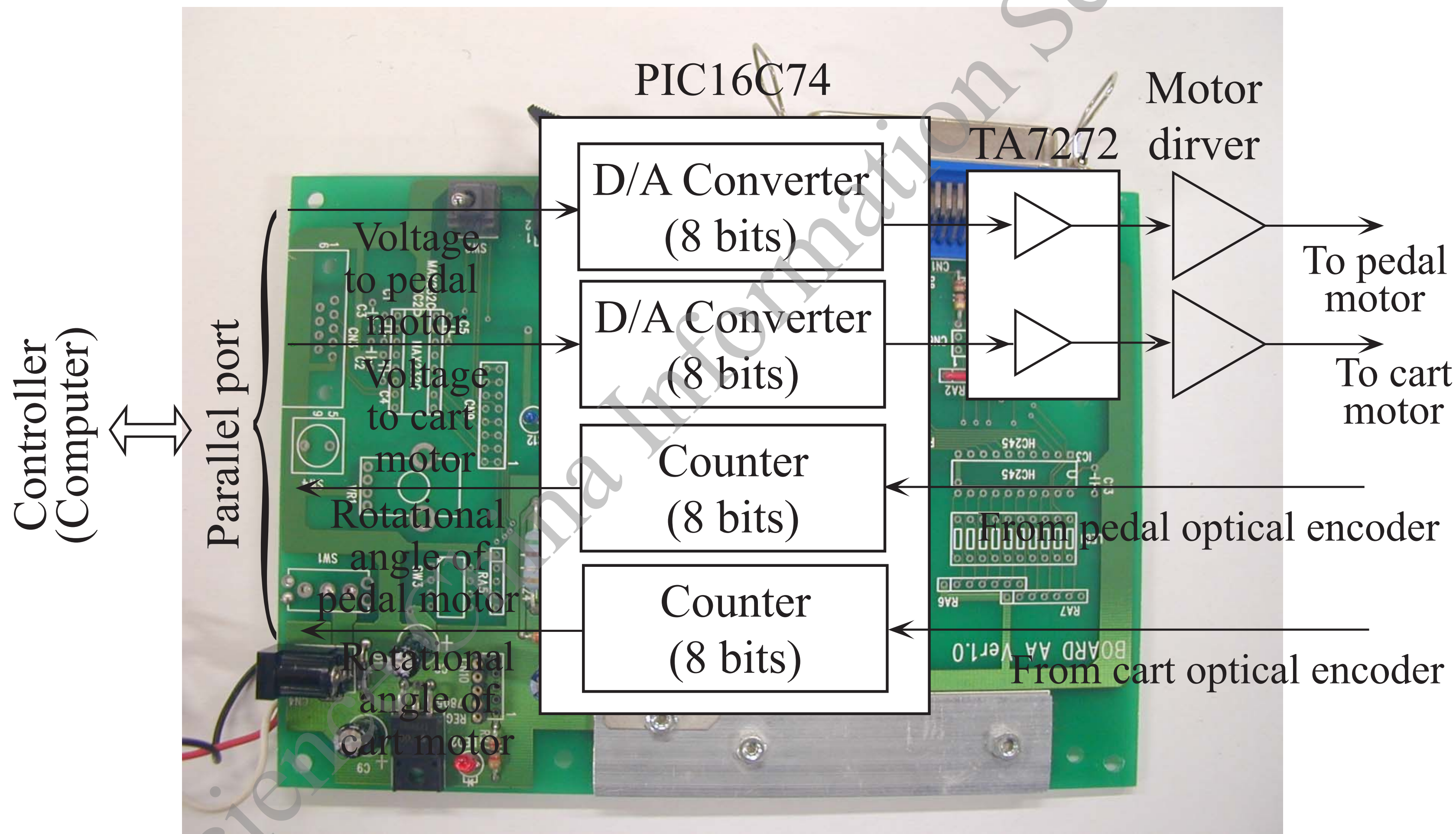


A Photo of New Electrical Cart

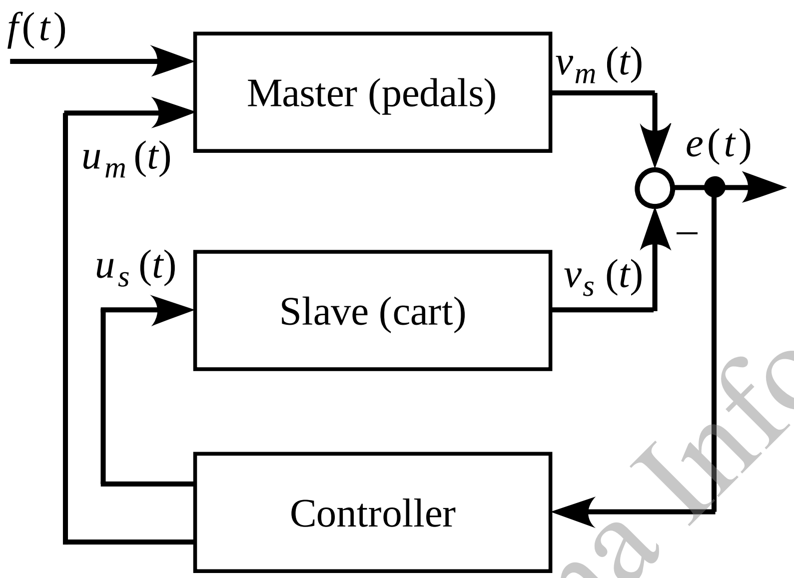


Everyday Type-S (Araco Corp., Japan)

Interface Board



Configuration of Bilateral Master-Slave Cart System (1)



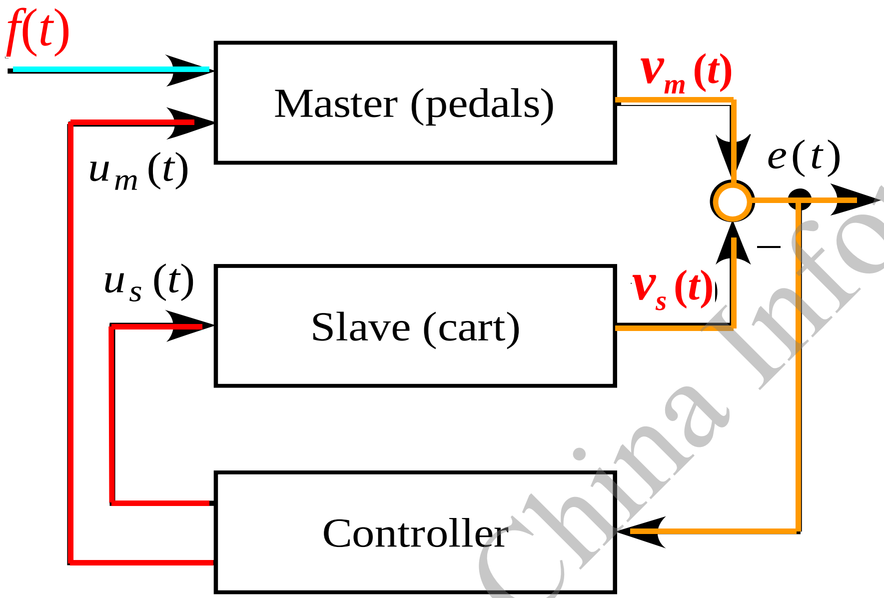
First-order plant is easy for humans to operate.

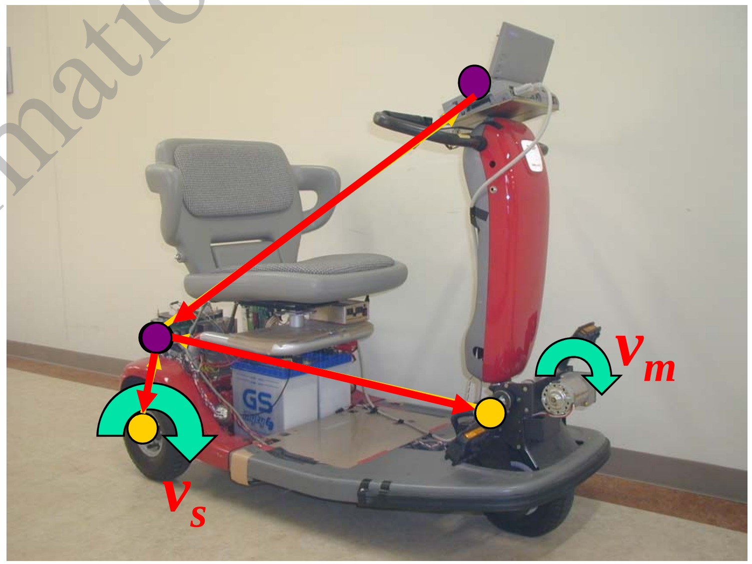
Controlled output: Speed

Reference input for cart: Speed of pedal motor

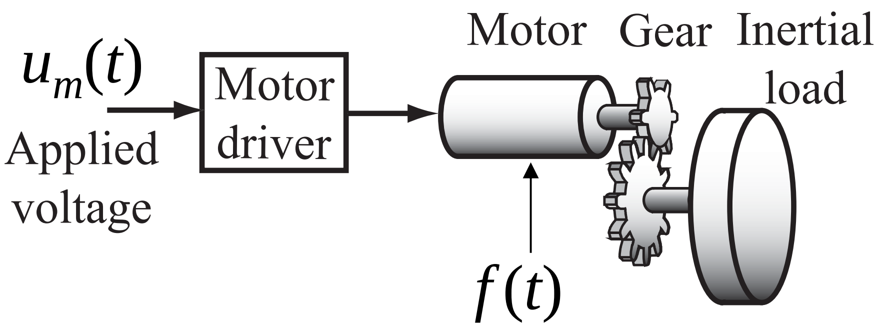
Speed of cart motor tracks speed of pedal motor

Configuration of Bilateral Master-Slave Cart System (2)





Modeling of Pedal and Cart



J_m: Moment of inertia of pedal motor
c_m: Frictional damping coefficient of pedal motor
k_m: Voltage gain of pedal driver

Pedal system:
$$\begin{cases} \frac{dv_m(t)}{dt} = A_m v_m(t) + B_m u_m(t) + B_f f(t), \\ A_m = \frac{c_m}{J_m},\quad B_m = \frac{k_m}{J_m},\quad B_\tau = \frac{1}{J_m}. \end{cases}$$

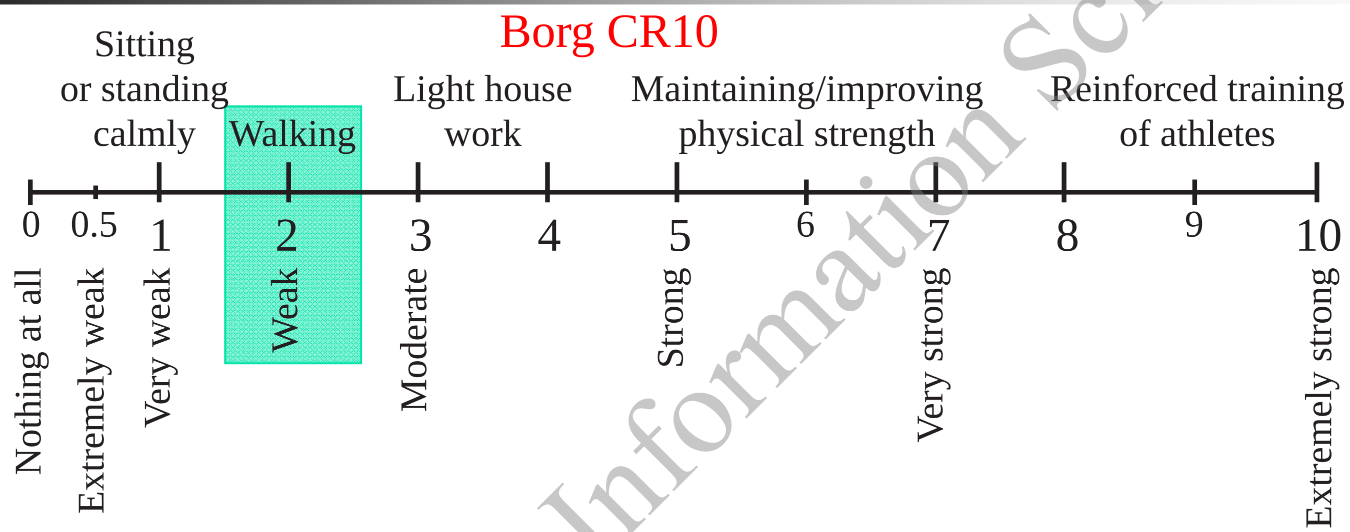
Cart system:
(Wt. of driver: 45 ~ 100 kg)
$$\begin{cases} \frac{dv_s(t)}{dt} = A_s v_s(t) + B_s u_s(t), \\ A_s(t) := A_{s0} + \Phi\Gamma\Psi_A, \\ B_s := B_{s0} + \Phi\Gamma\Psi_B, \\ \Gamma^2 \leq 1. \end{cases}$$

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):

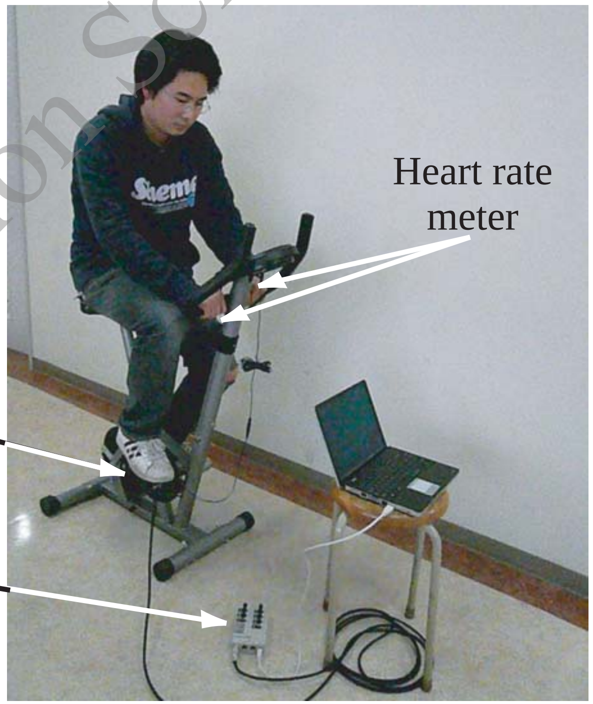
$$r_{Ht} = r_{Hr} + r_{PE}(r_{Hm} - r_{Hr})$$

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: $f_{max} = 40$ N

Introduction of an Impedance Model

Impedance Model:

Describes feeling of pushing pedals.

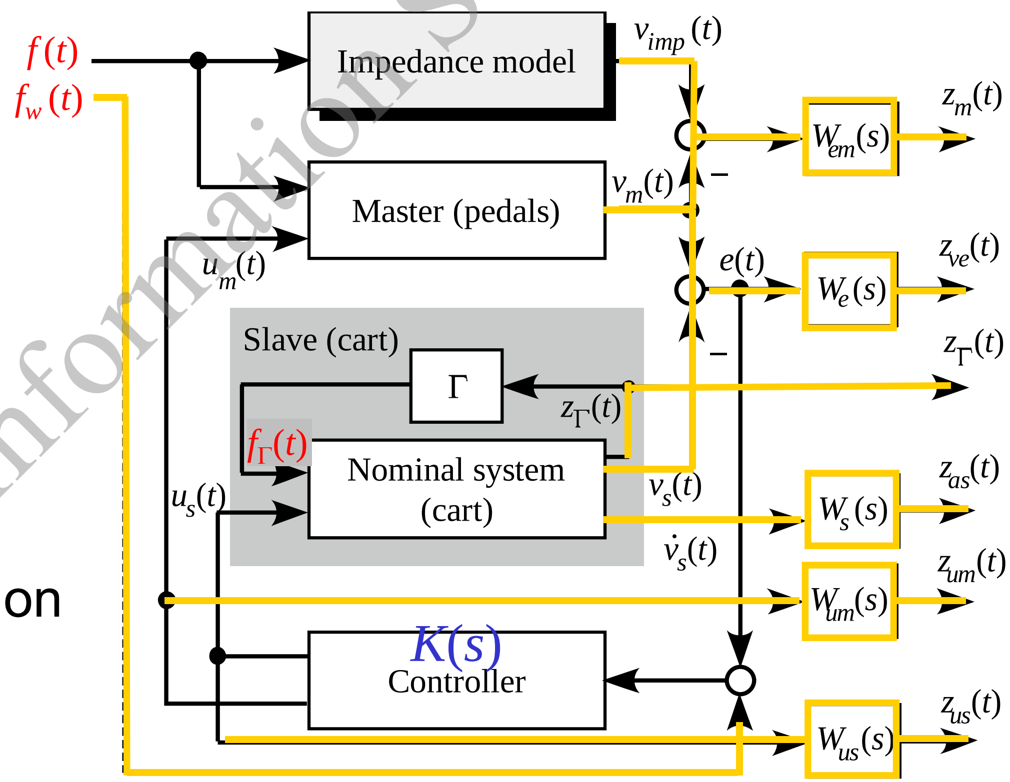
$$\frac{dv_p(t)}{dt} = A_p v_p(t) + B_p f(t)$$

Mode	A_p	B_p
Strenuous	–1.49	2.00
Neutral	–1.49	3.49
Assisted	–1.49	3.90

Formulation of Control Problem

Find a controller $K(s)$ such that

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

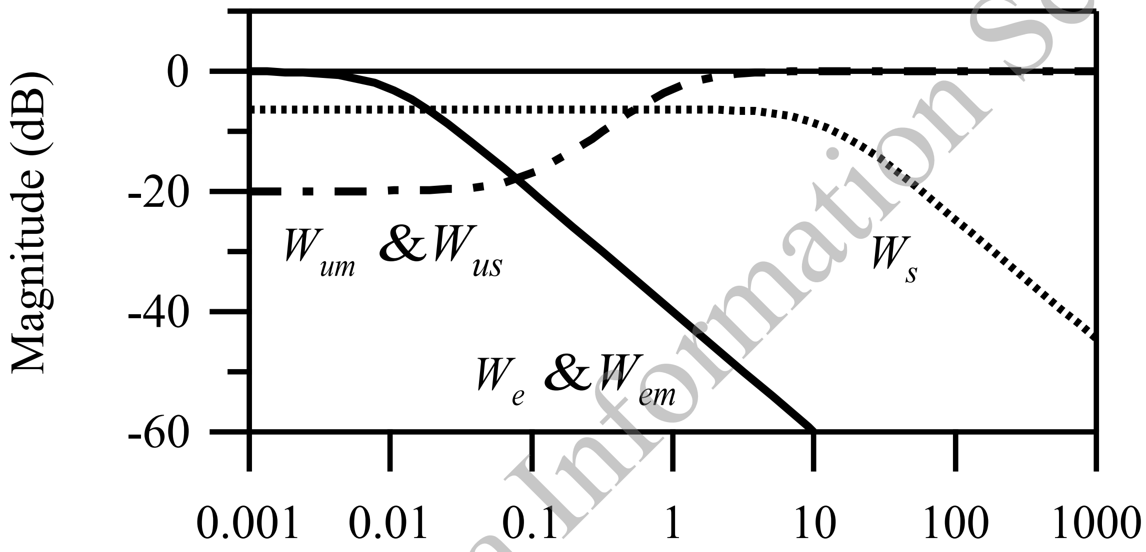


$f_w(t)$: Relaxes the solvable condition

$$w(t) = [f(t)\ \ f_\Gamma(t)\ \ f_w(t)]^\top$$

$$z(t) = [z_m(t)\ \ z_{ve}(t)\ \ z_\Gamma(t)\ \ z_{as}(t)\ \ z_{us}(t)\ \ z_{um}(t)]^\top$$

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

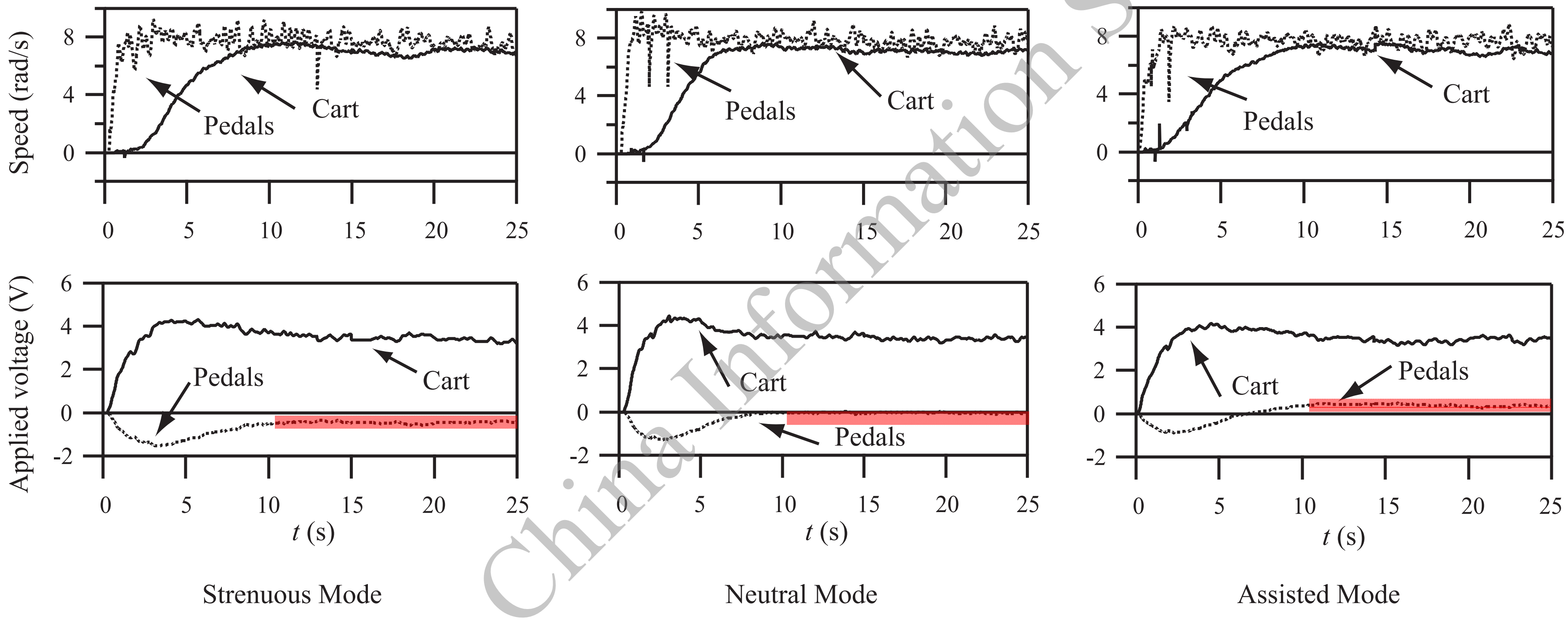
Road conditions:

flat road
5^{o} uphill slope
5^{o} downhill slope

Weight of driver:

47 ~ 70 kg

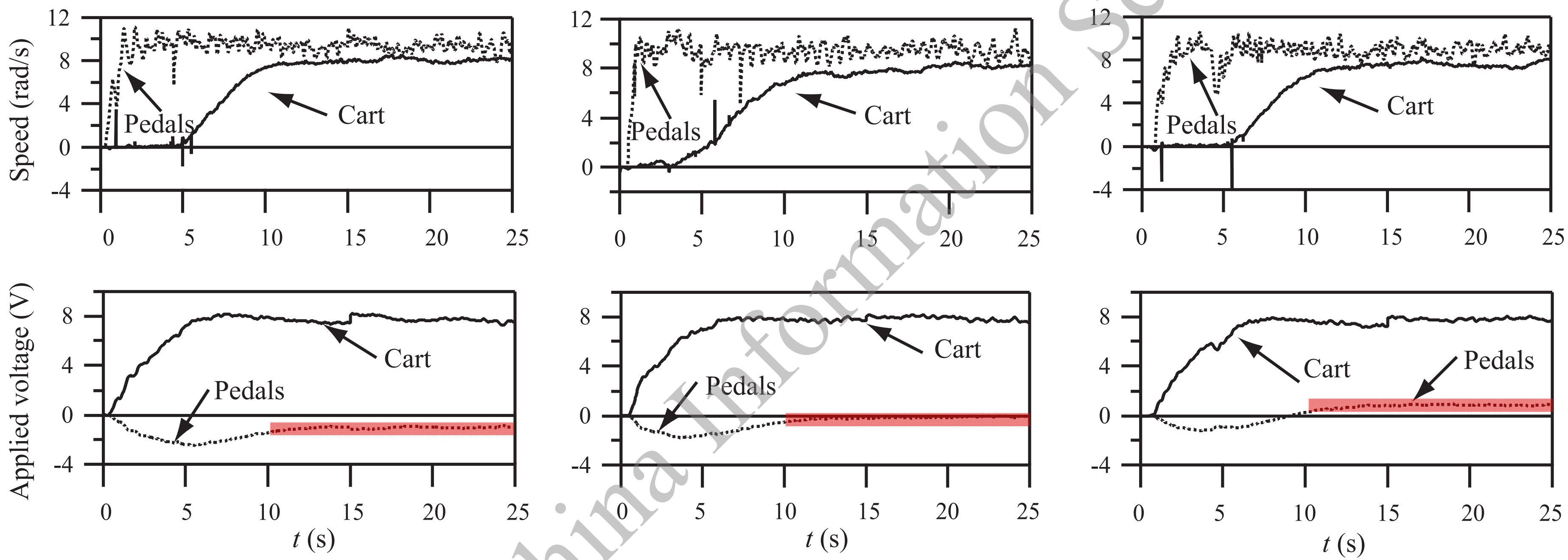
Exp. Results 1: Flat Road



$u_{m\ avg(15-25)} = -0.462$ V $\quad u_{m\ avg(15-25)} = -0.047$ V $\quad u_{m\ avg(15-25)} = 0.377$ V

Weight of driver: 63 kg

Exp. Results 2: Uphill Slope

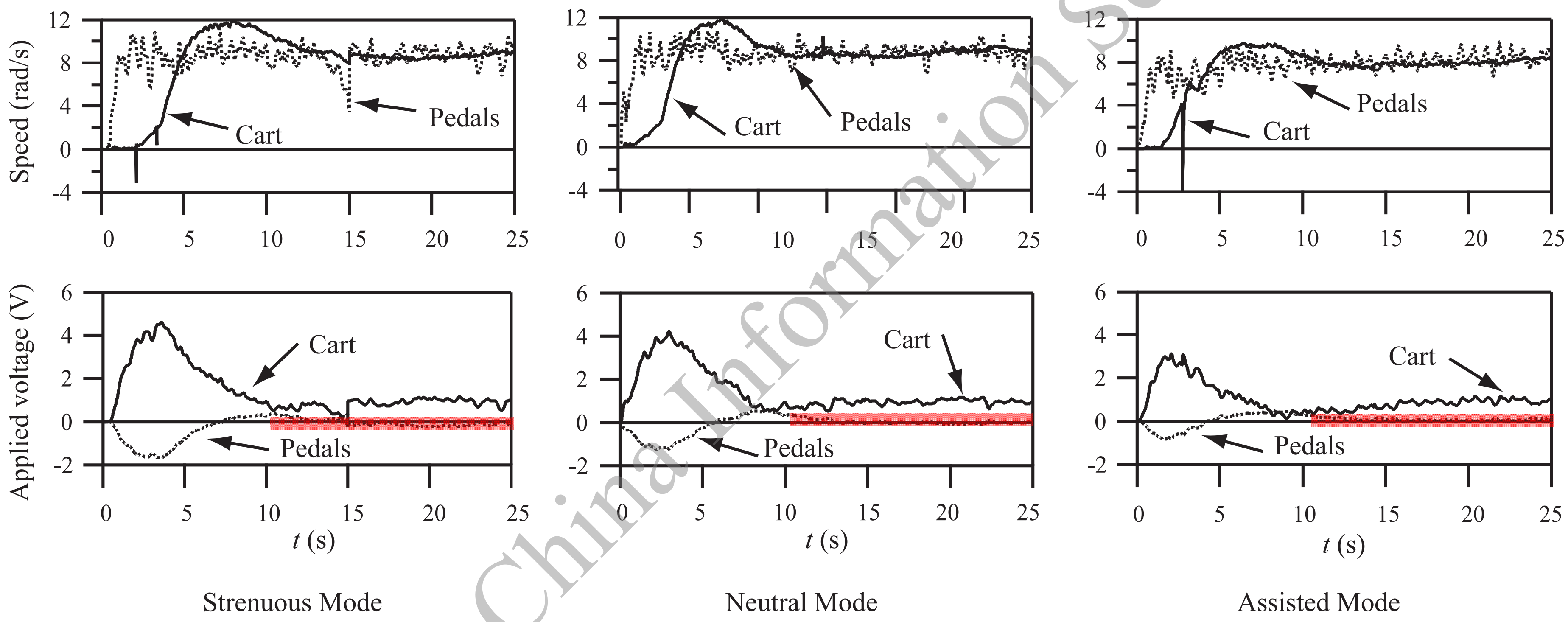


Strenuous Mode | Neutral Mode | Assisted Mode

$u_{m\ avg(15-25)} = -0.993$ V $u_{m\ avg(15-25)} = -0.088$ V $u_{m\ avg(15-25)} = 0.866$ V

Weight of driver: 63 kg

Exp. Results 3: Downhill Slope



$u_{m\ avg(15-25)} = -0.105$ V

$u_{m\ avg(15-25)} = 0.003$ V

$u_{m\ avg(15-25)} = 0.097$ V

Weight of driver: 63 kg

Controller Design

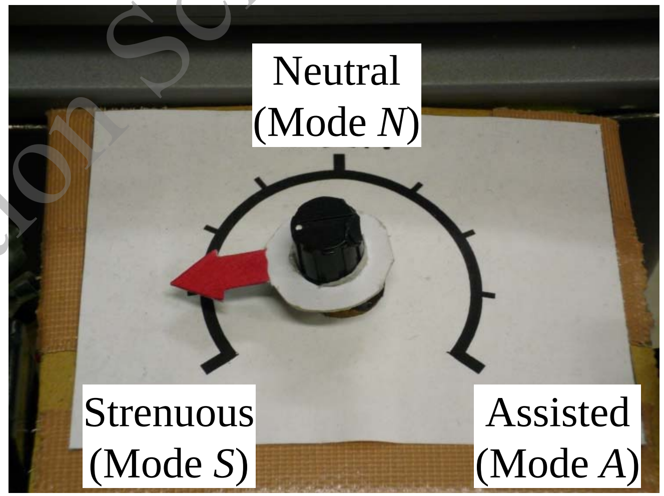
Step 2

Design of controller for a selected load

Load Adjusting Function

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

Mode	Controller	Control input
Strenuous	C_S	u_S
Neutral	C_N	u_N
Assisted	C_A	u_A



Designed controllers: C_S , C_N , C_A

Dynamic parallel distributed compensation

Automatic generation of controller for any level of load/assistance

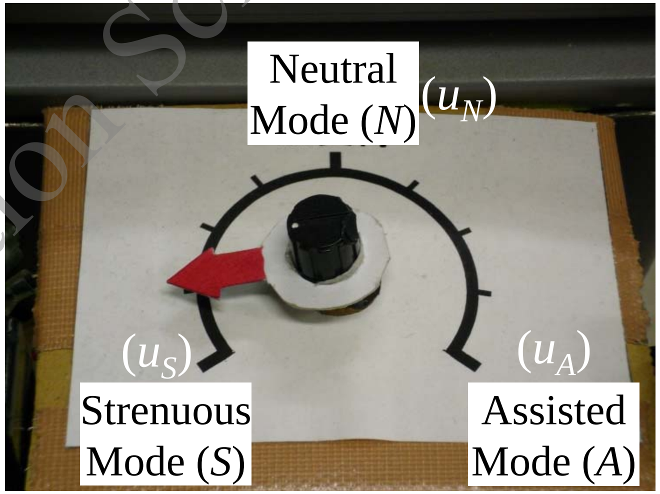
Gain-Scheduling Control System for Any Level of Load/Assistance (2)

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

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

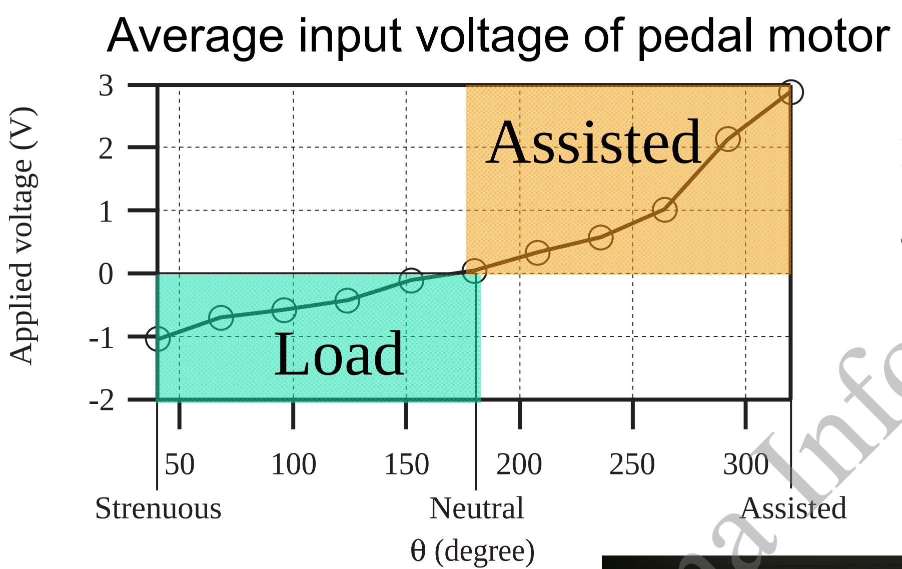


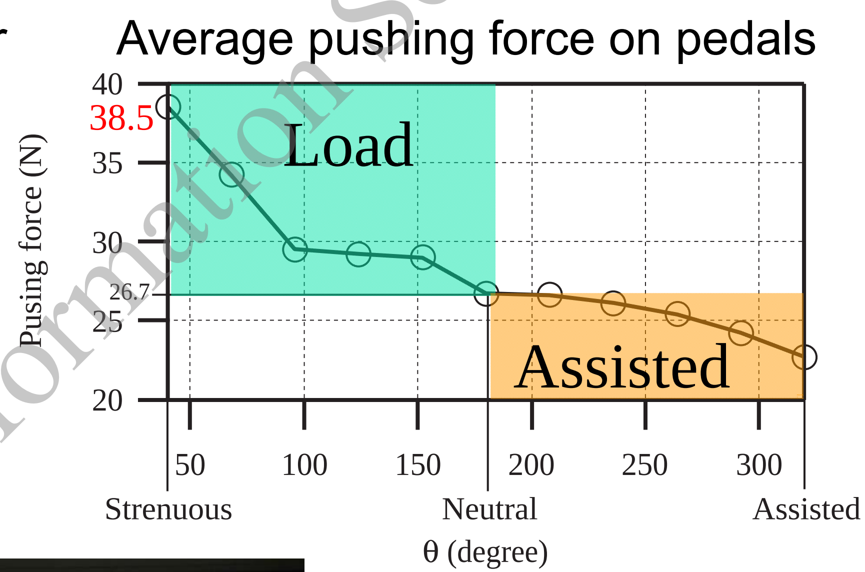
The above control law guarantees the stability of the closed-loop cart control system if there exists a common symmetric positive definite matrix P such that the following hold:

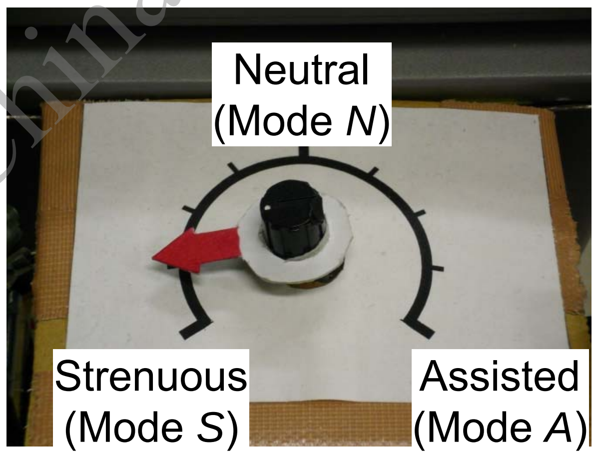
$$P\bar{A}_S(\Gamma) + \bar{A}_S^\top(\Gamma)P < 0,$$
$$P\bar{A}_N(\Gamma) + \bar{A}_N^\top(\Gamma)P < 0,$$
$$P\bar{A}_A(\Gamma) + \bar{A}_A^\top(\Gamma)P < 0.$$

$\bar{A}_i(\Gamma)\ (i = S, N, A)$: System matrix of the closed-loop system

Experimental Results (Flat Road)





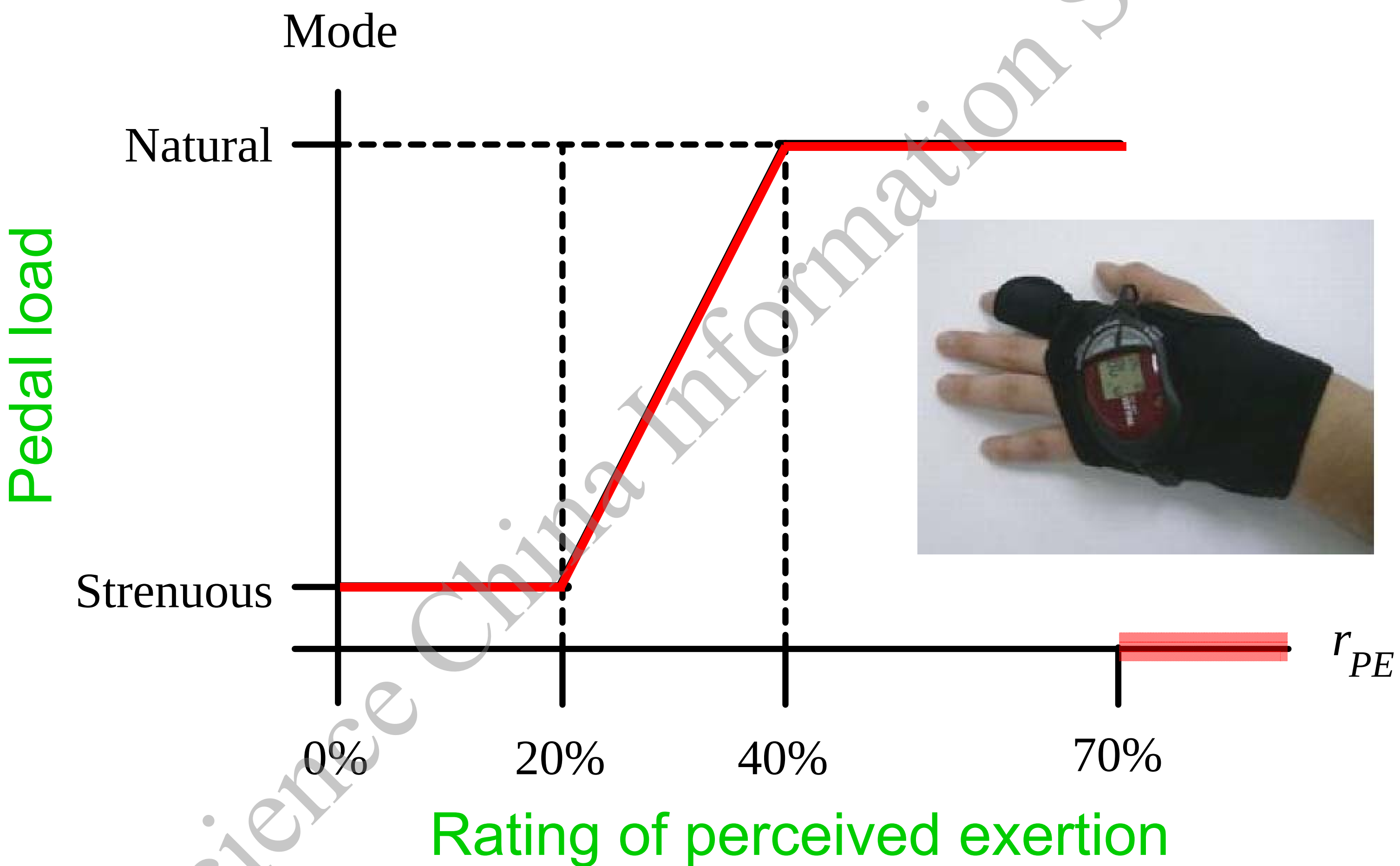


Controller Design

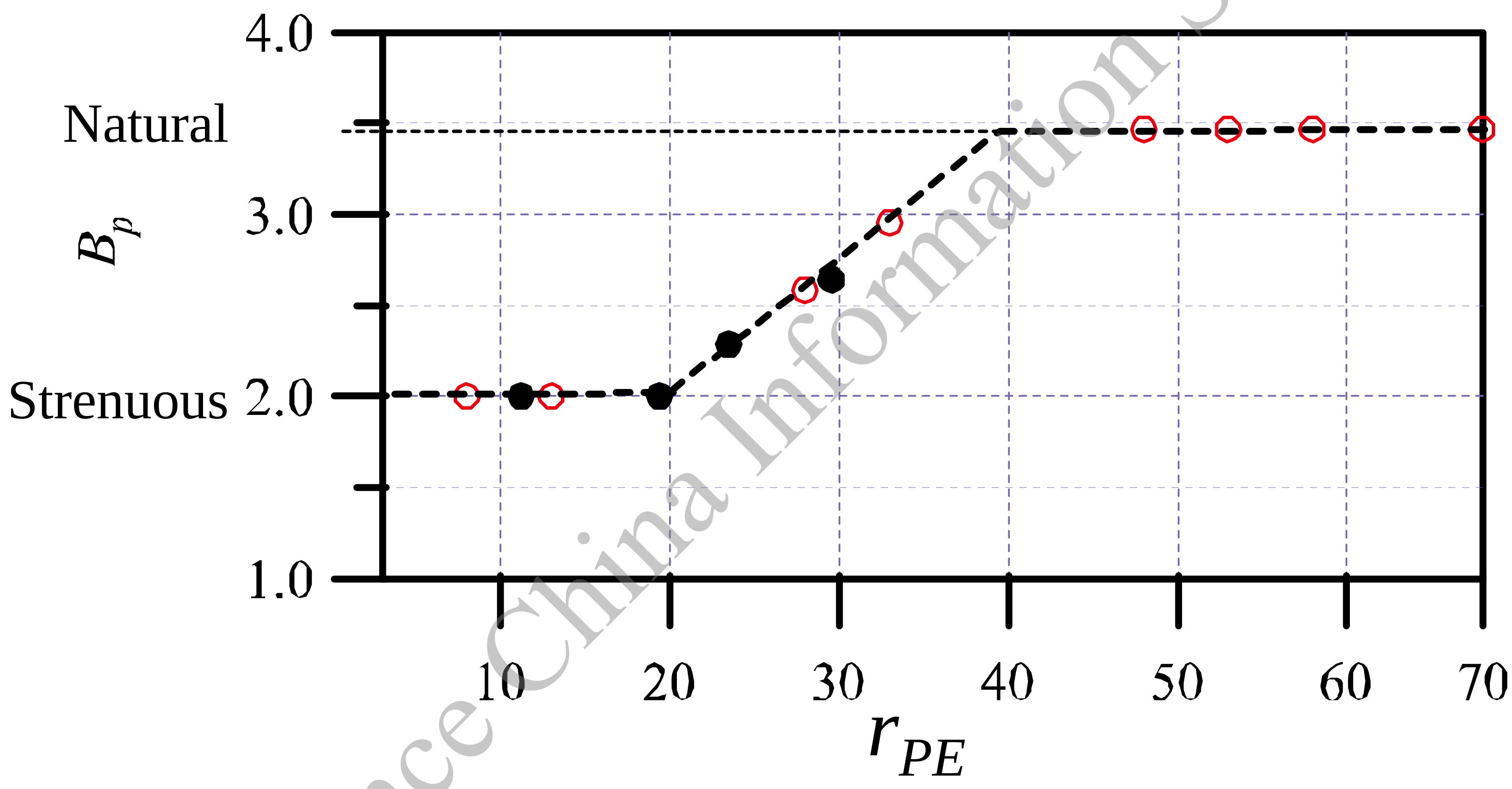
Step 3

Automatic selection of a load

Automatic Selection of Pedal Load

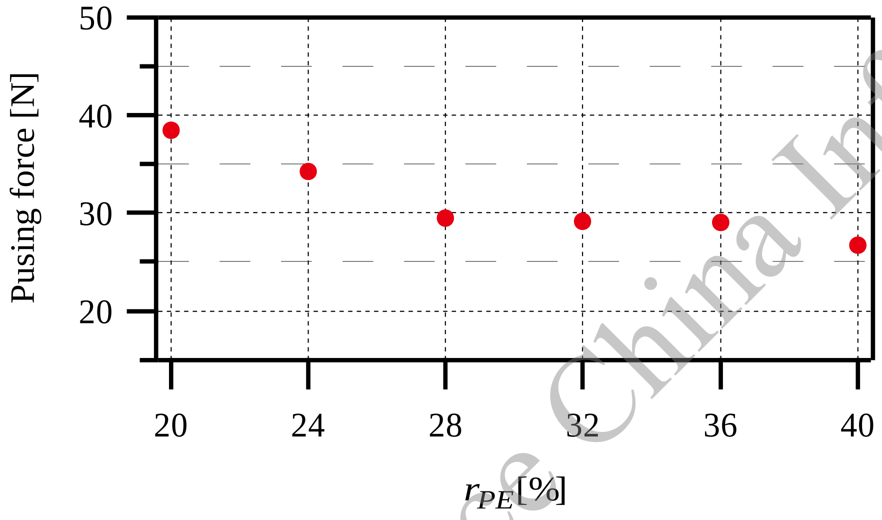


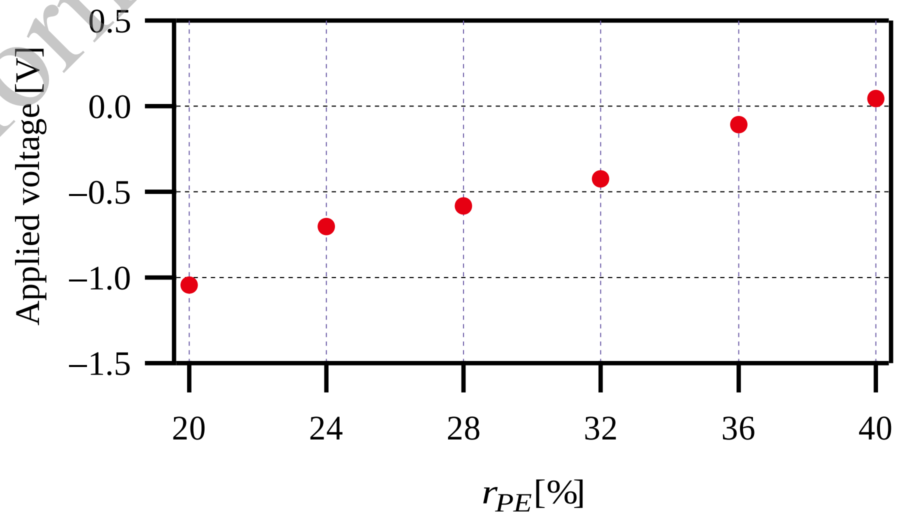
Exp. Results: B_p vs. r_{PE}



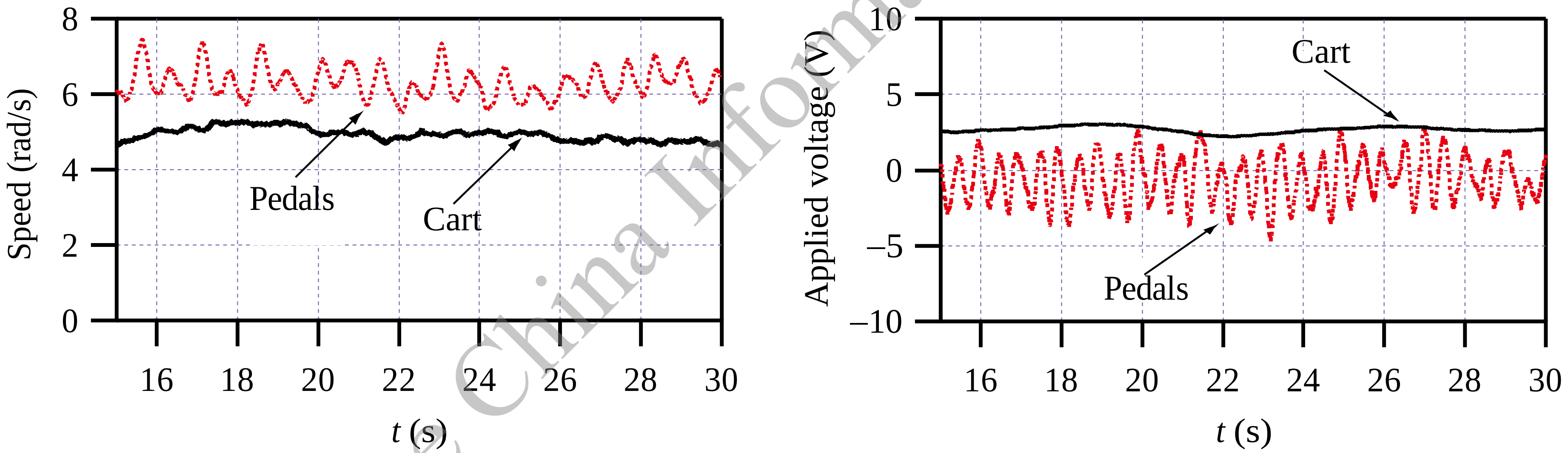
O: Subject 1 (21 years old), ●: Subject 2 (83 years old)

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_∞ 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