A New Concept Electric Cart for Maintaining/Improving Physical Strength

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

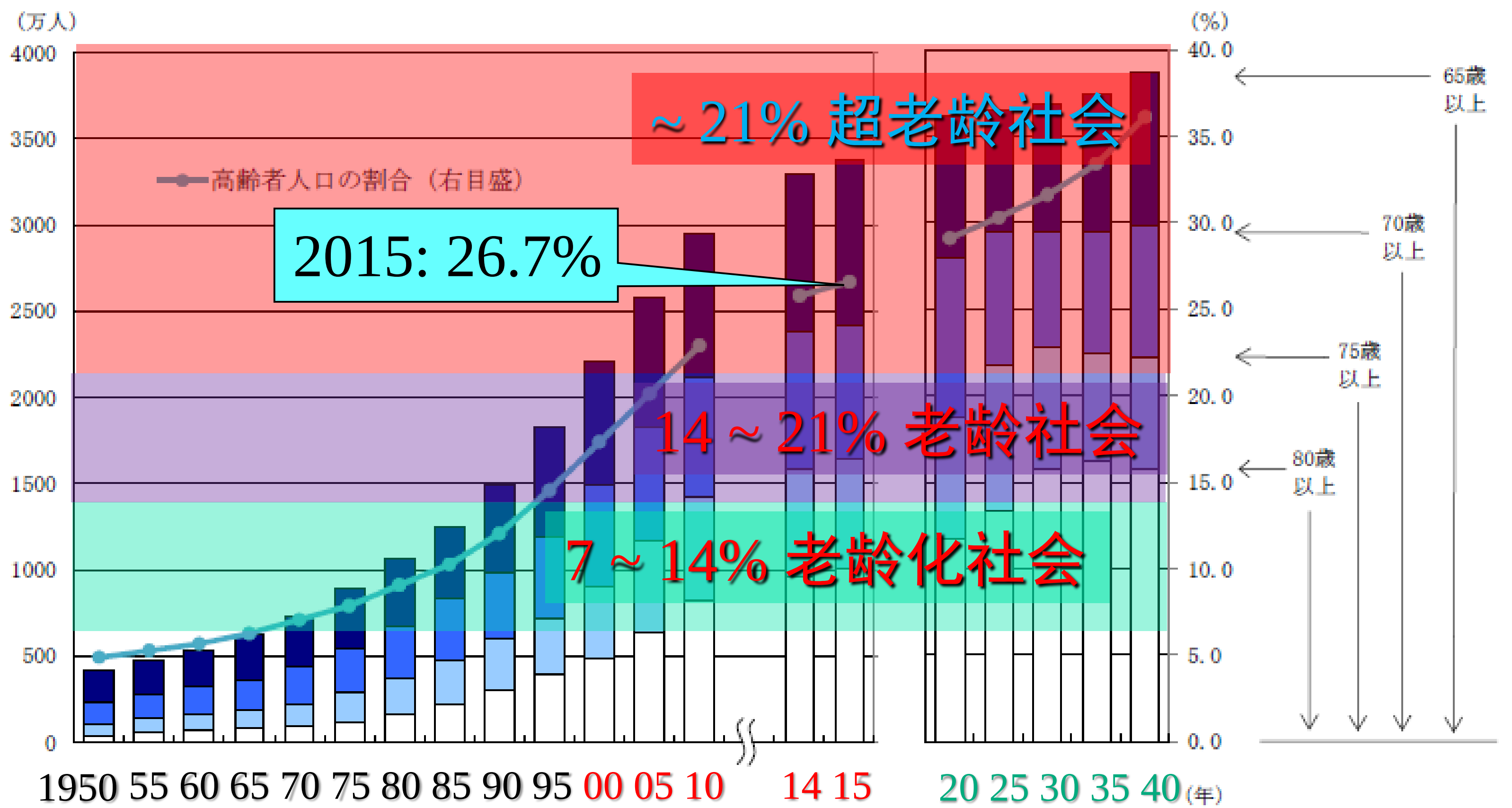
Jinhua She
China University of Geosciences (Wuhan)

Outline

- Background
- Measures for Aging Society from Japanese Government
- System Configuration of Electric Cart
- Design of Controller
  - 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
- Experimental Results

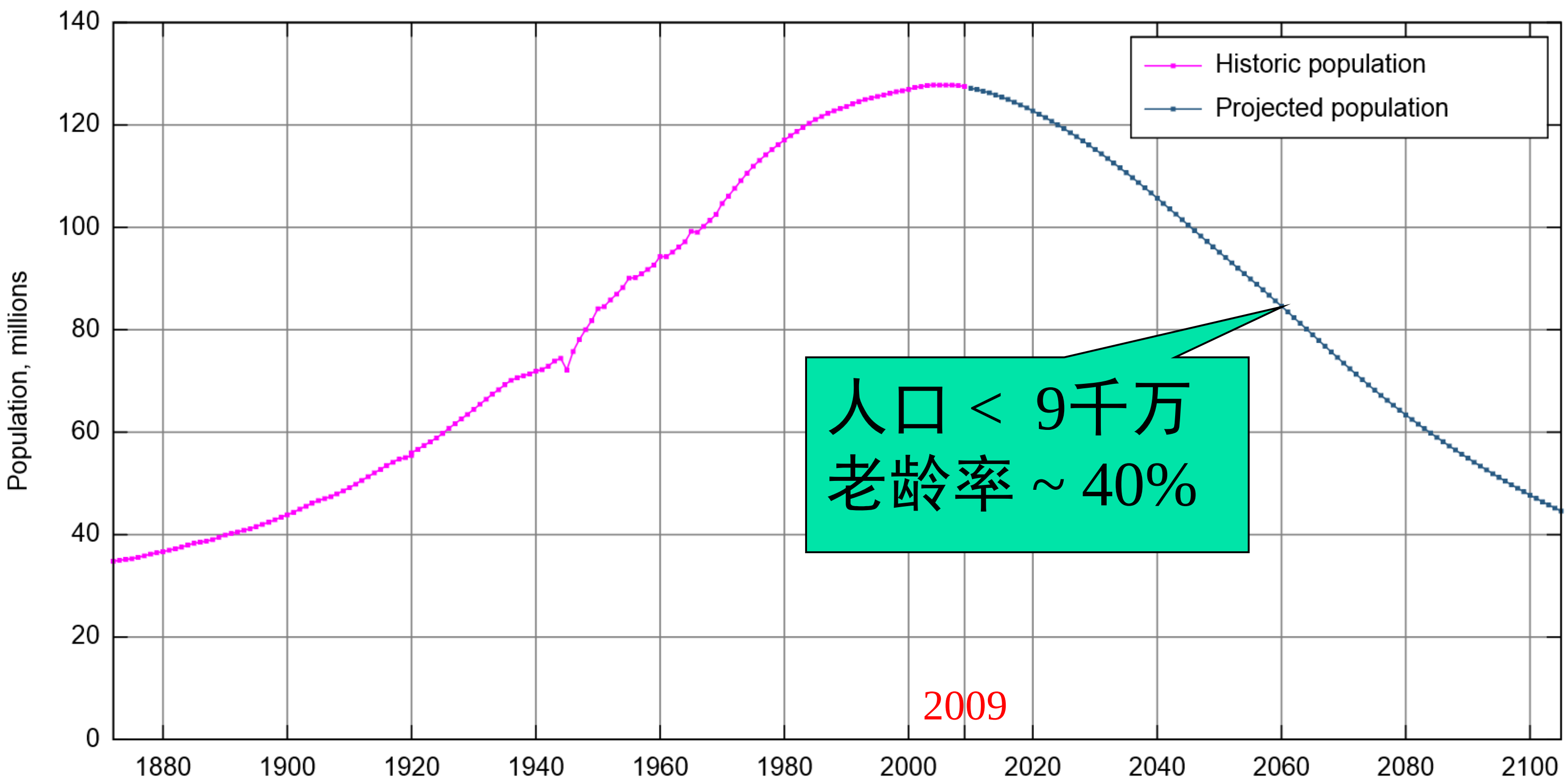
Aging in Japan

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



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

Demography of Japan



From: 日本总务省统计局

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

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Priority Areas

- 机器人护理机械开发的重点领域
  - 换乘护理
  - 移动支援
  - 排泄支援
  - 老年痴呆患者的介护
  - 入浴支援

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

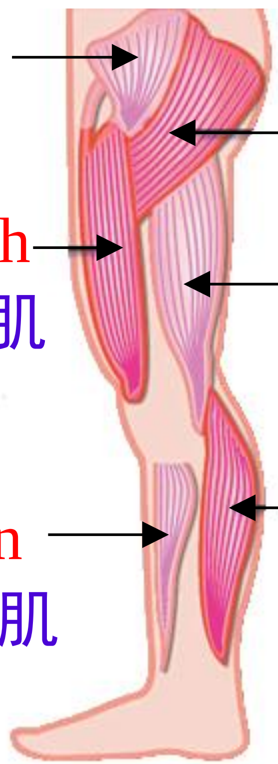
- Volume of brachial-flexor muscles
  - Men: 200 ~ 300 cm^3 Women: 150 ~ 200 cm^3

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

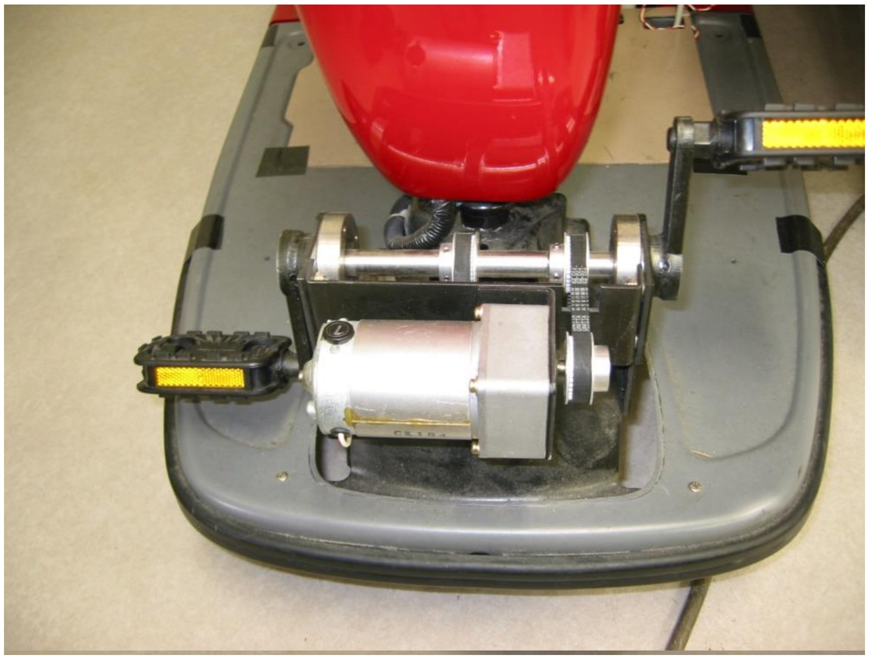
- Walking muscles need exercise.
- Cycling is the ideal exercise to work the muscles.

  Pedal down: front thigh (大腿四头肌), calf (小腿三头肌), and hamstring (大腿二头肌)

  Pedal up: loin (腰肌), front thigh (大腿四头肌), and shin (颈骨肌)

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:

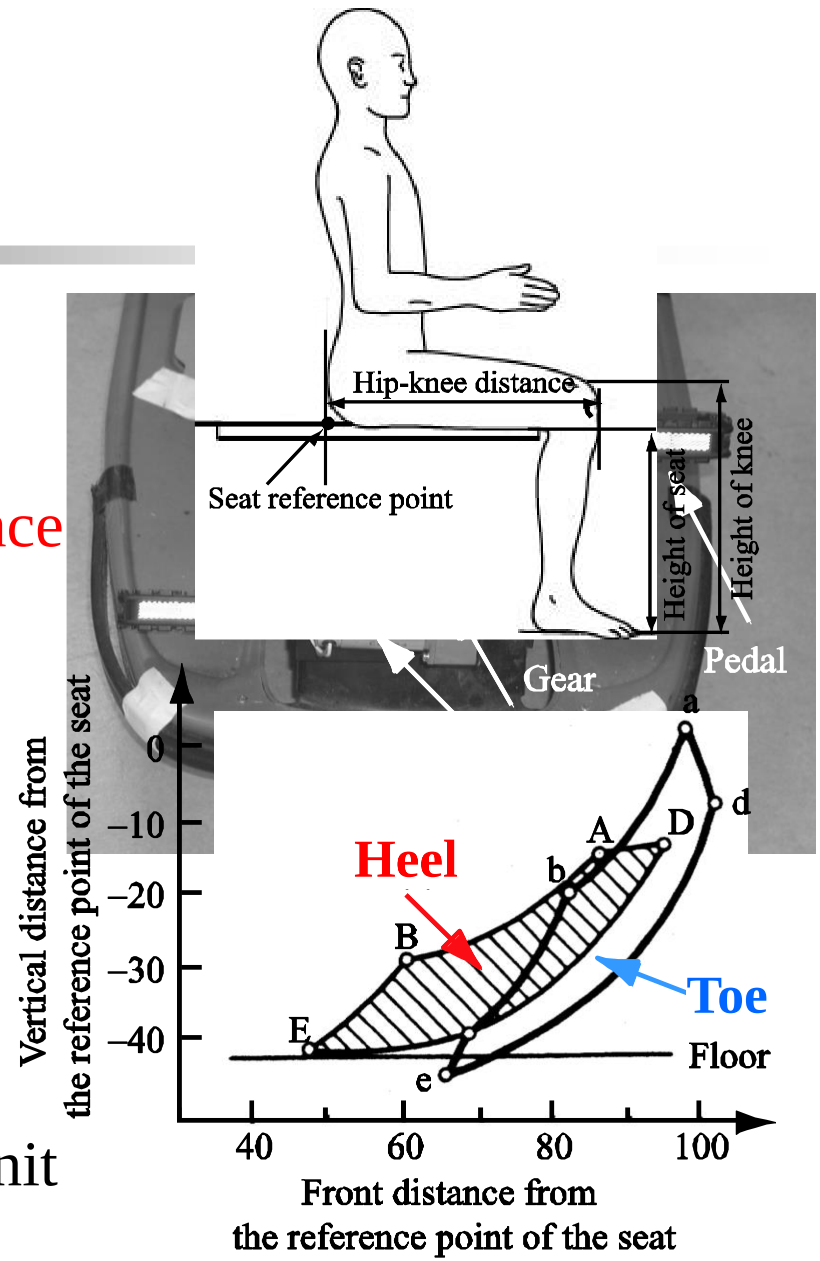
  Responsive to road conditions:

  More realistic driving experience

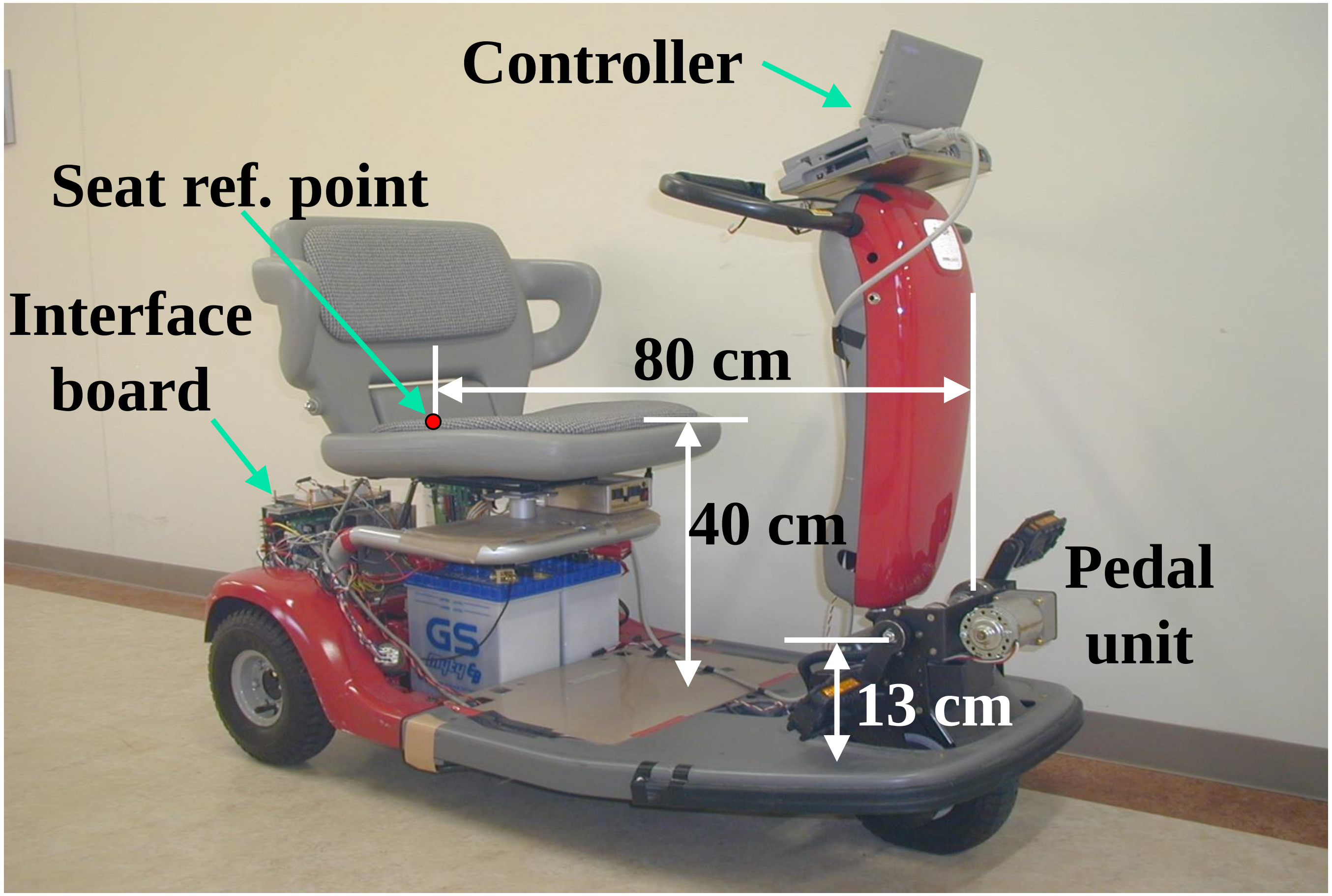
- Installation:

  Optimal pedaling region

Ergonomic mounting of seat and pedal unit

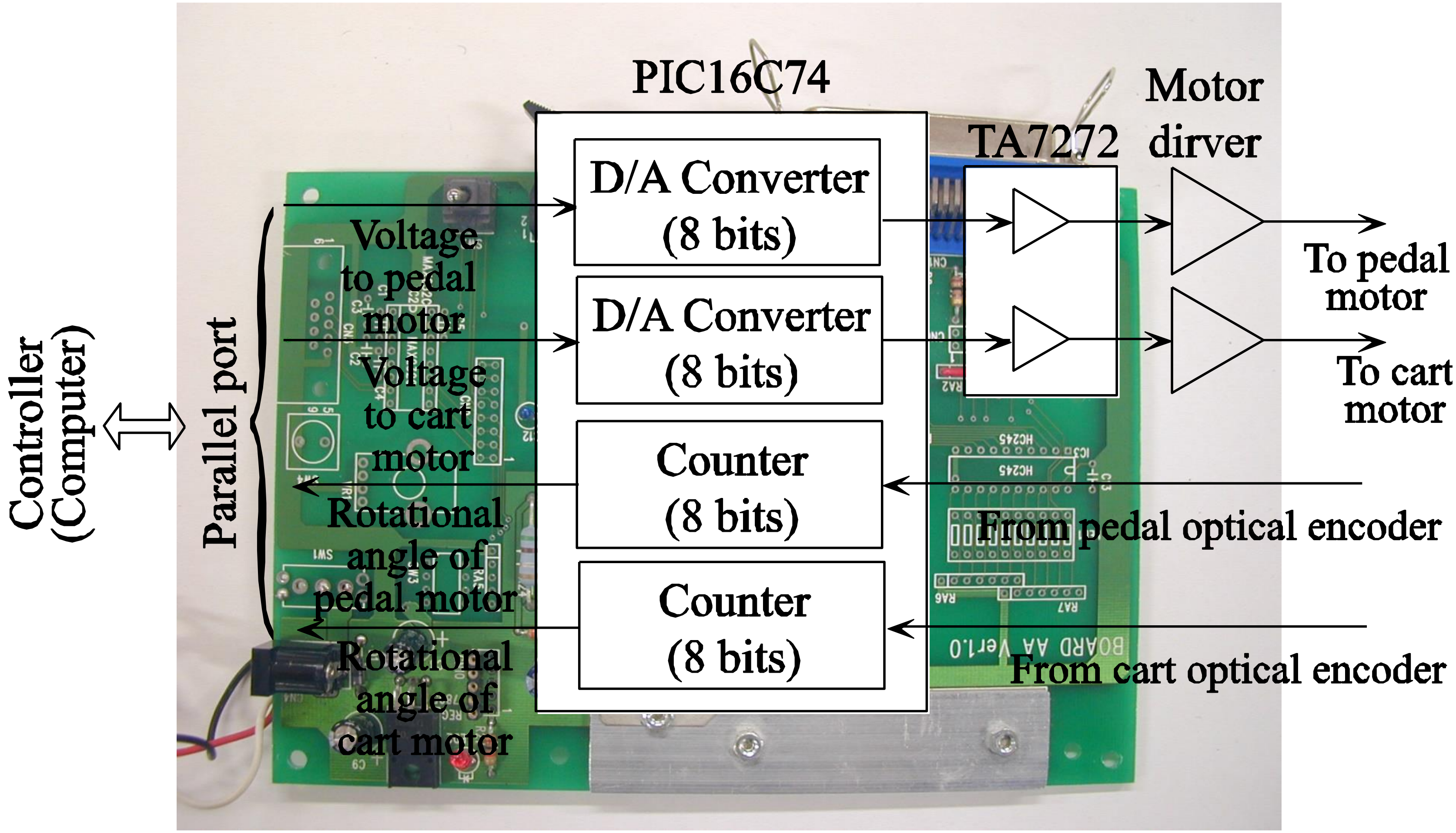


A Photo of New Electrical Cart

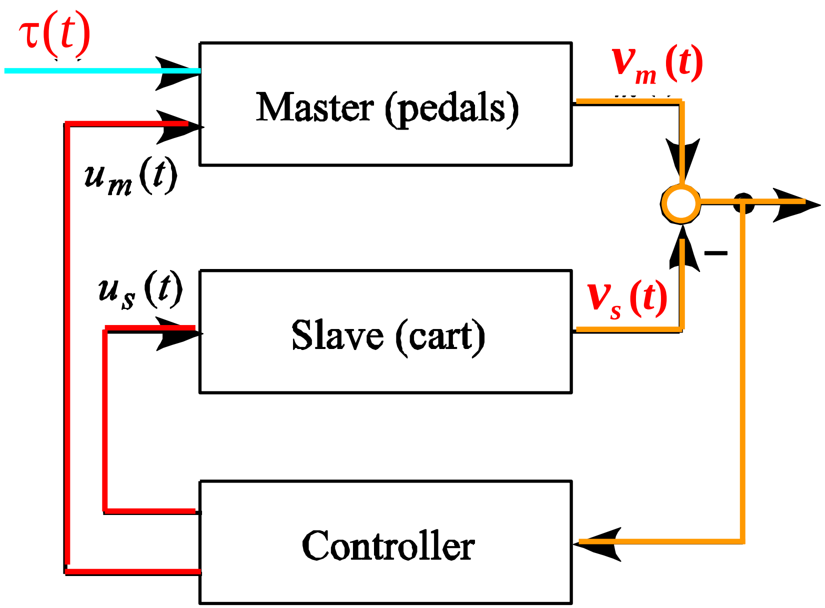


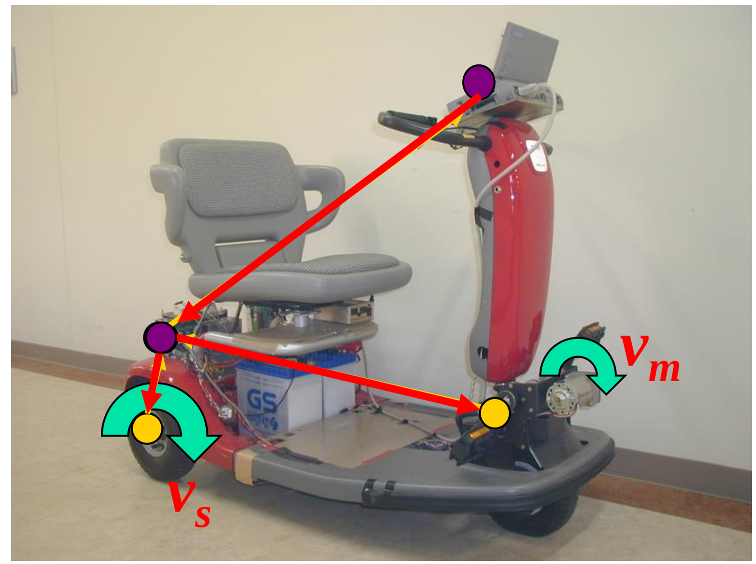
Everyday Type-S (Araco Corp., Japan)

Interface Board



Configuration of Bilateral Master-Slave Cart System (1)

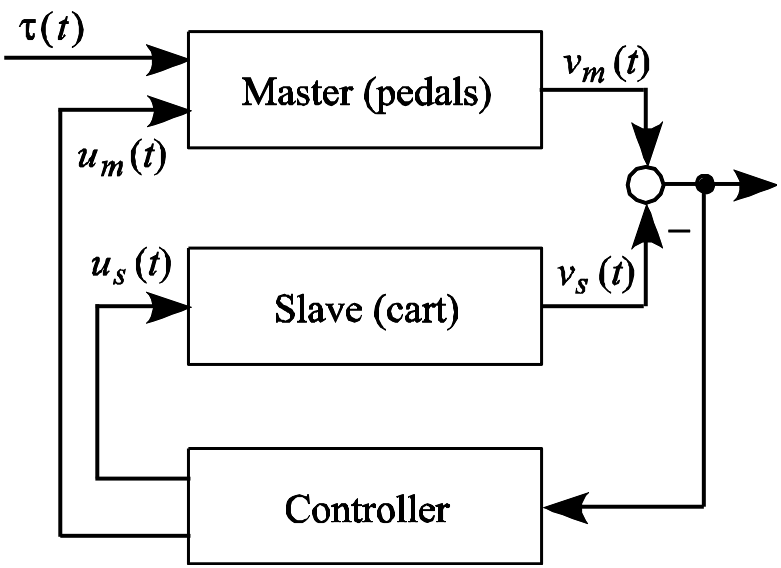




Reference input for cart: Rotational angular speed of pedal motor

Rotational angular speed of cart motor tracks angle of pedal motor

Configuration of Bilateral Master-Slave Cart System (2)



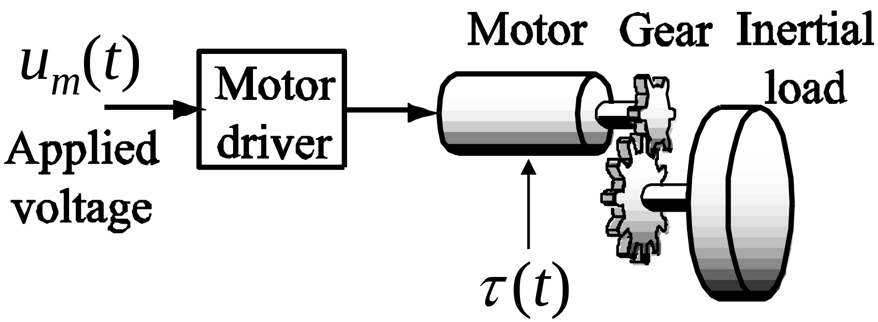
First-order plant is easy for humans to operate.

Controlled output: Speed

Reference input for cart: Speed of pedal motor

Speed of cart motor tracks speed of pedal motor

Modeling of Pedal and Cart



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

Pedal system:

$$\begin{cases} \dfrac{dv_m(t)}{dt} = A_m v_m(t) + B_m u_m(t) + \overbrace{B_\tau \tau(t)}^{\tau'(t)}, \\ A_m = \dfrac{c_m}{J_m}, \quad B_m = \dfrac{k_m}{J_m}, \quad B_\tau = \dfrac{1}{J_m}. \end{cases}$$

Cart system:
(Wt. of driver: 45 ~ 100 kg)

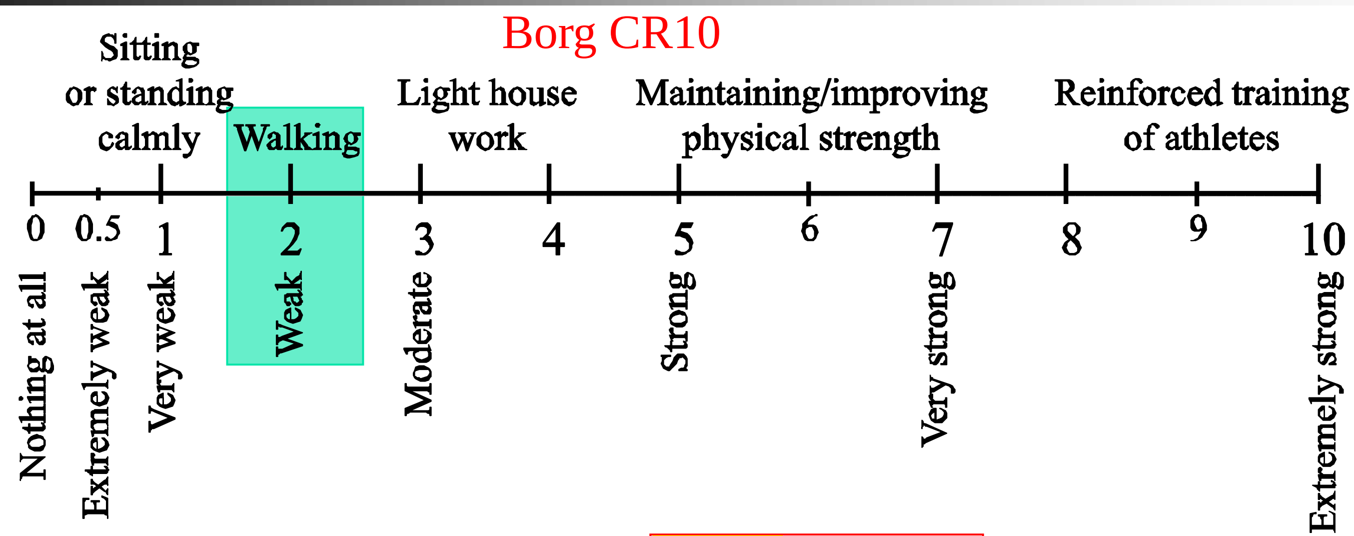
$$\begin{cases} \dfrac{dv_s(t)}{dt} = A_s v_s(t) + B_s u_s(t), \\ A_s(t) := A_{s0} + \Phi \Gamma(t) \Psi_A, \\ B_s := B_{s0} + \Phi \Gamma(t) \Psi_B, \\ \Gamma^2(t) \leq 1. \end{cases}$$

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):

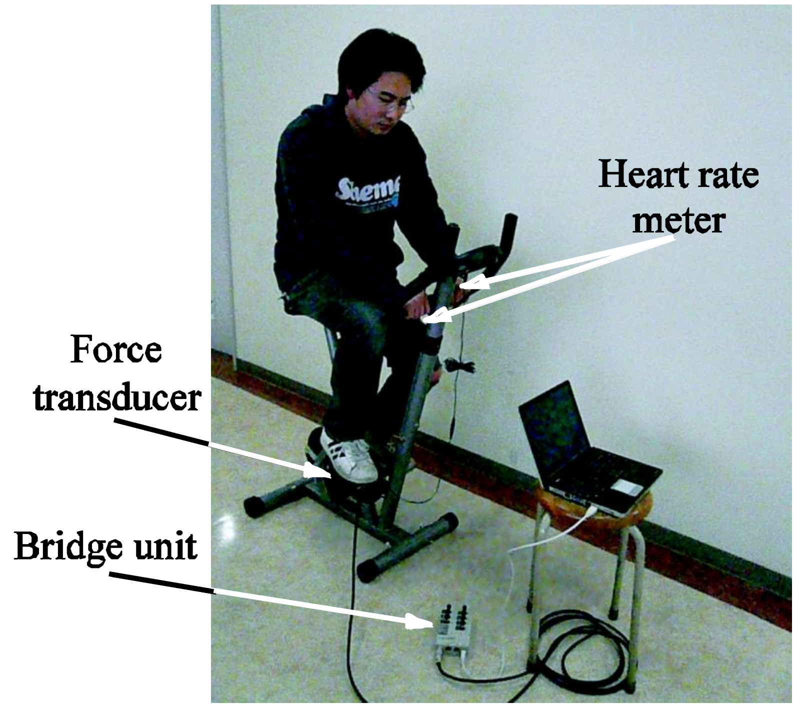
$$r_{Ht} = r_{Hr} + r_{PE}(r_{Hm} - r_{Hr})$$

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.

$$\frac{dv_p(t)}{dt} = A_p v_p(t) + B_p \tau'(t)$$

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

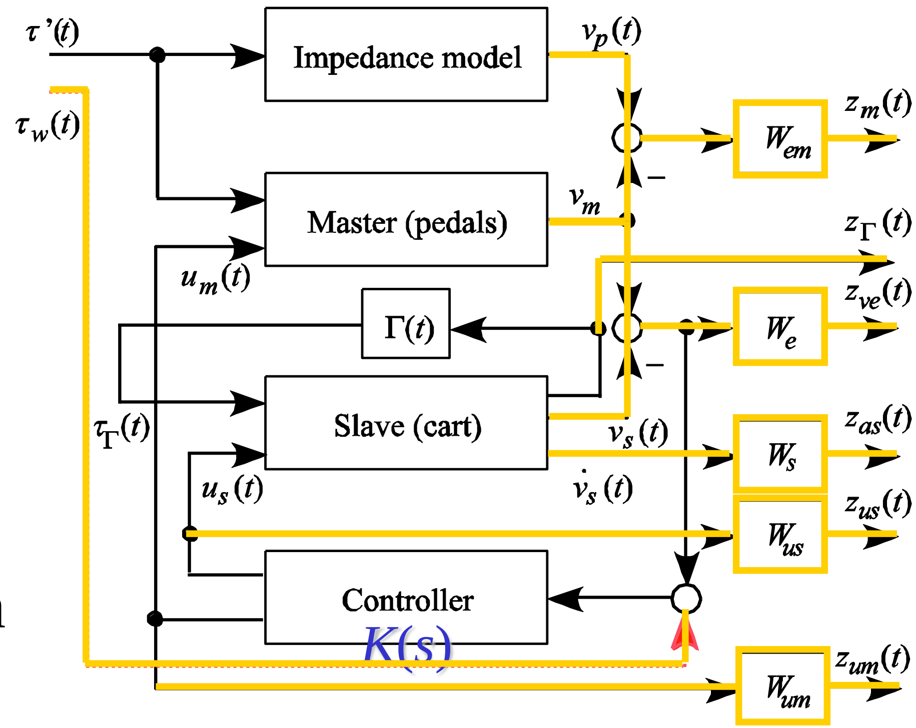
Formulation of Control Problem

Find a controller $K(s)$ such that

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

$\tau_w(t)$:

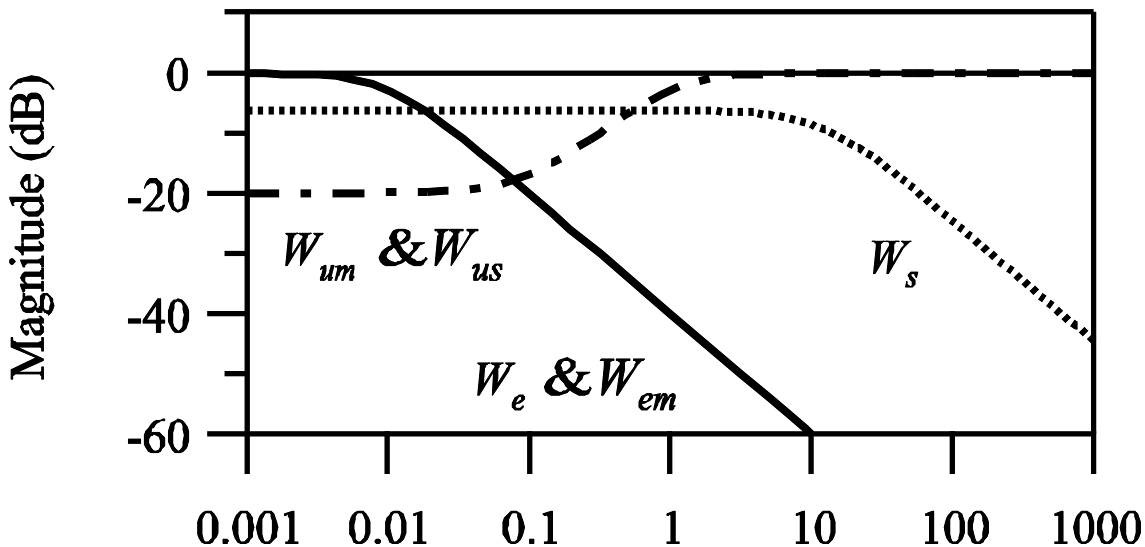
Relaxes the solvable condition



$$w(t) = [\tau'(t)\ \ \tau_\Gamma(t)\ \ \tau_w(t)]^T$$

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

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

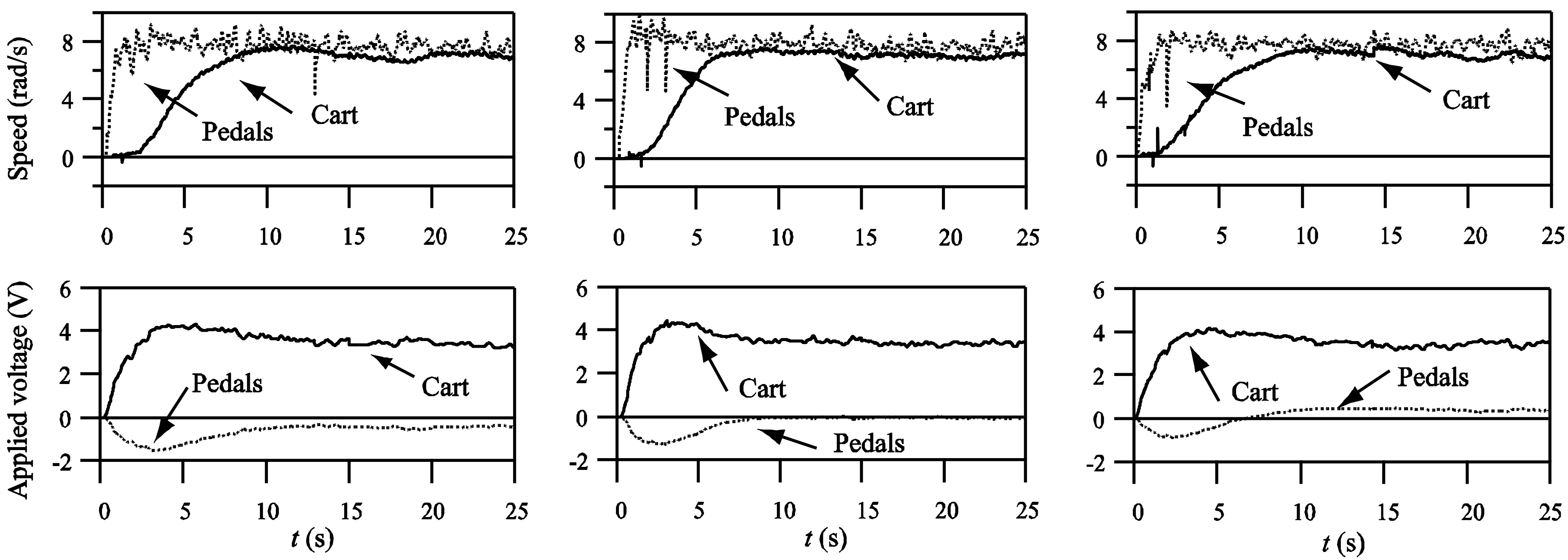
5 °downhill slope

Weight of driver:

47 ~ 70 kg

Experiments

Exp. Results 1: Flat Road



Strenuous Mode

$$u_{m\ avg(15-25)} = -0.462\ \mathrm{V}$$

Neutral Mode

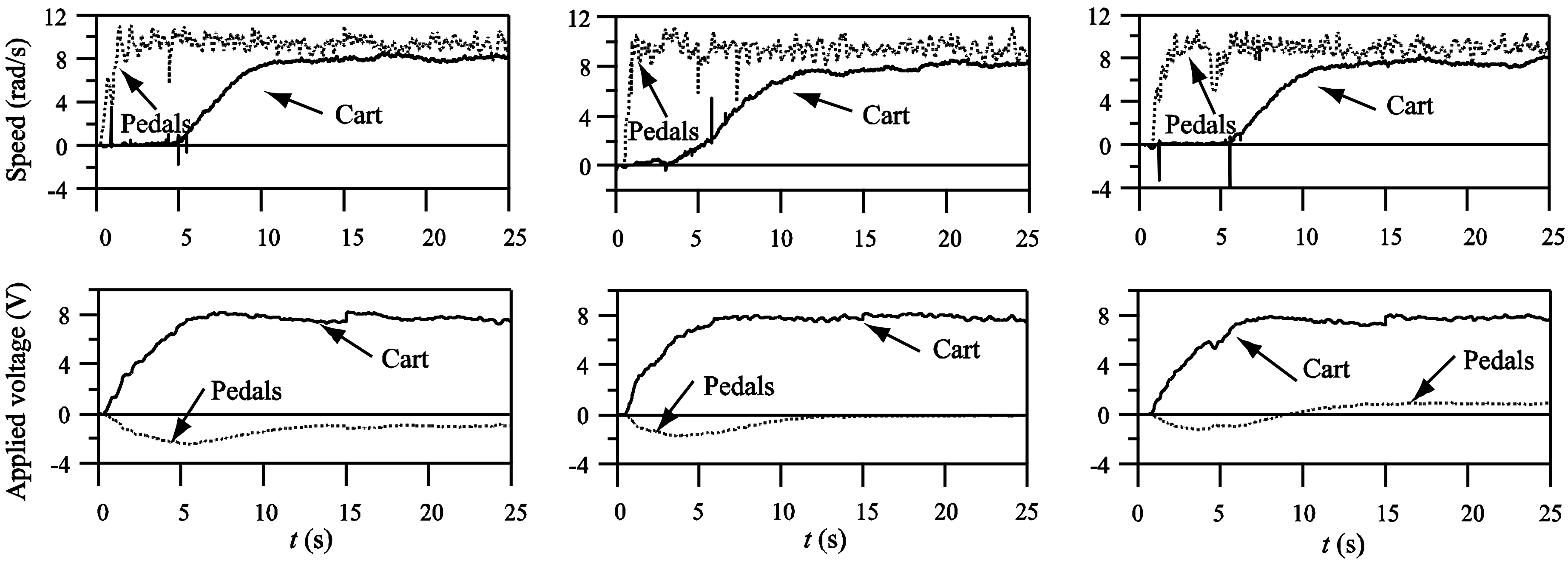
$$u_{m\ avg(15-25)} = -0.047\ \mathrm{V}$$

Assisted Mode

$$u_{m\ avg(15-25)} = 0.377\ \mathrm{V}$$

Weight of driver: 63 kg

Exp. Results 2: Uphill Slope



Strenuous Mode | Neutral Mode | Assisted Mode

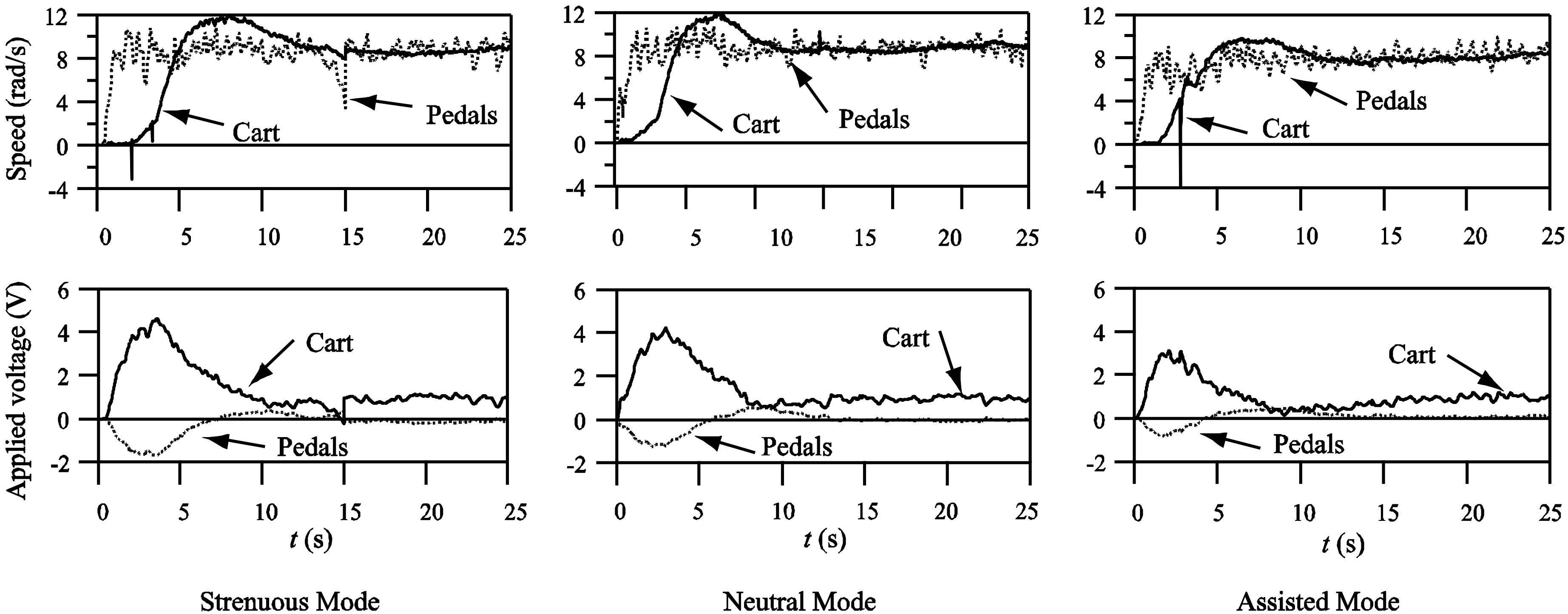
$u_{m\ avg(15-25)} = -0.993$ V

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

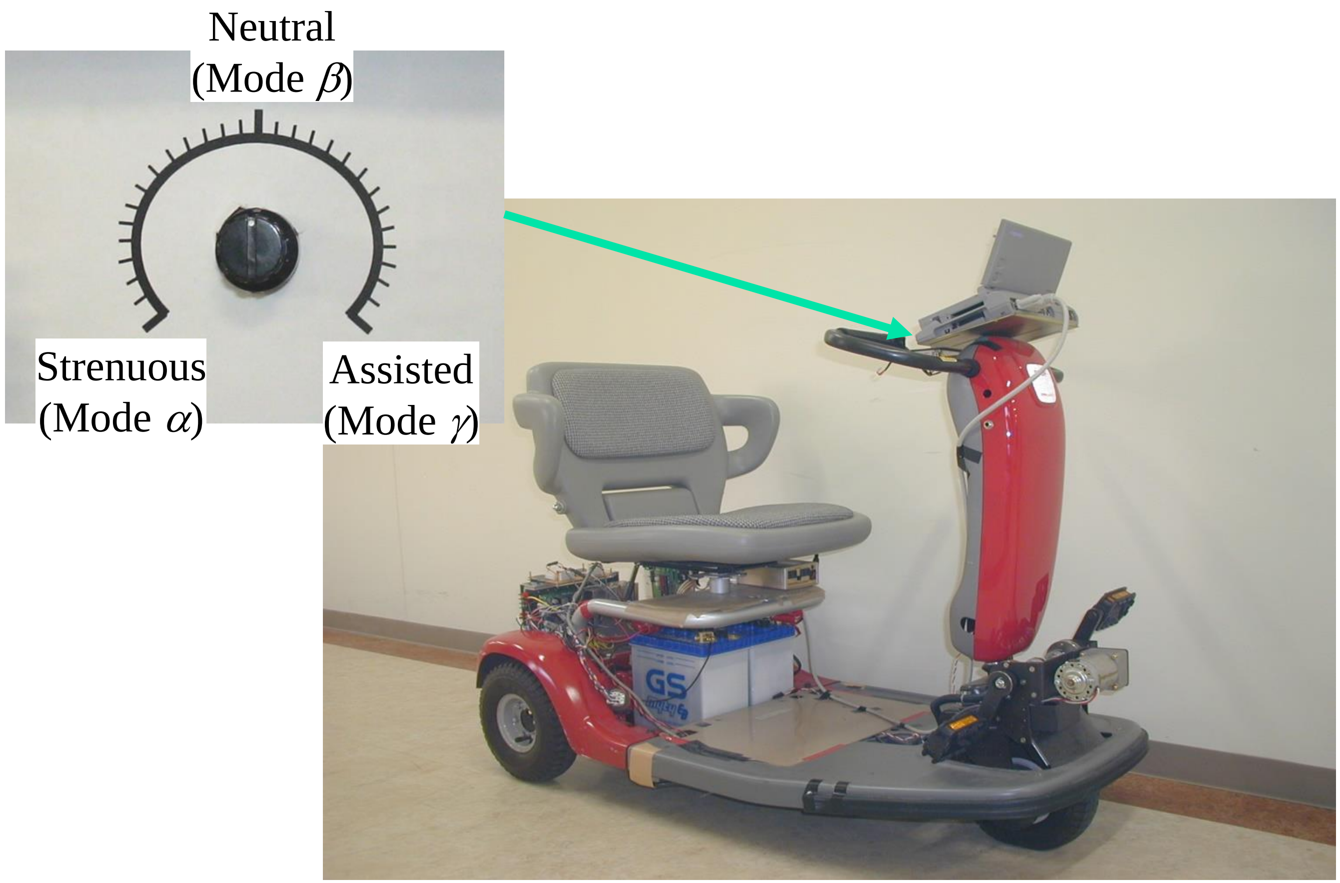
Weight of driver: 63 kg

Controller Design

Step 2

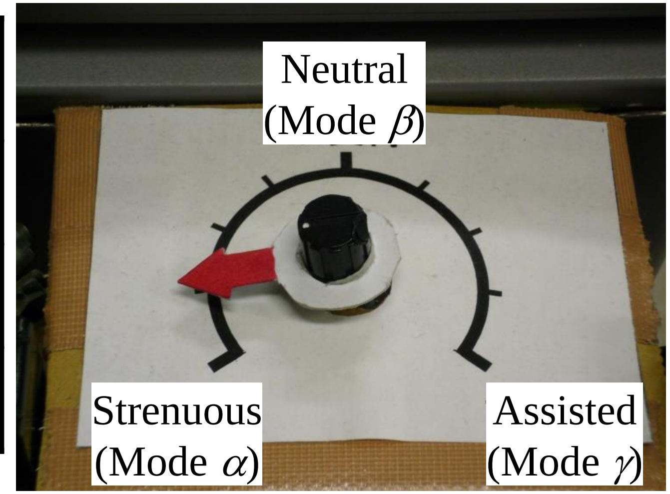
Design of controller for a selected load

Load Adjusting Function



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

Mode	Controller	Control input
Strenuous	C_α	u_α
Neutral	C_β	u_β
Assisted	C_γ	u_γ



Designed controllers: C_α, C_β, C_γ

Dynamic parallel distributed compensation

Automatic generation of controller for any level of load/assistance

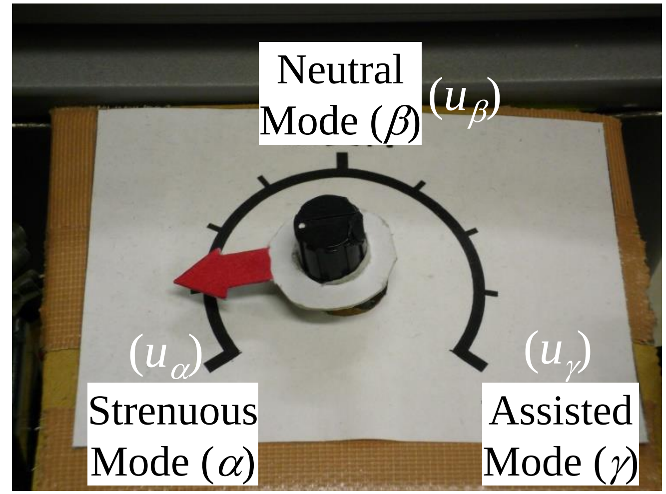
Gain-Scheduling Control System for Any Level of Load/Assistance (2)

Control input:

$$u(t) = \lambda_\alpha u_\alpha(t) + \lambda_\beta u_\beta(t) + \lambda_\gamma u_\gamma(t)$$

$\lambda_\alpha, \lambda_\beta, \lambda_\gamma$: Coefficients

$(\lambda_\alpha + \lambda_\beta + \lambda_\gamma = 1)$

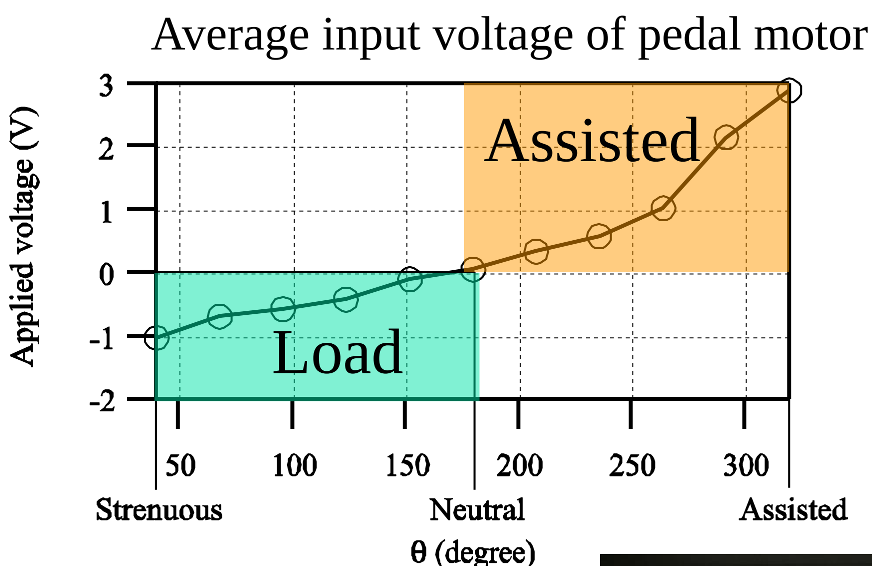


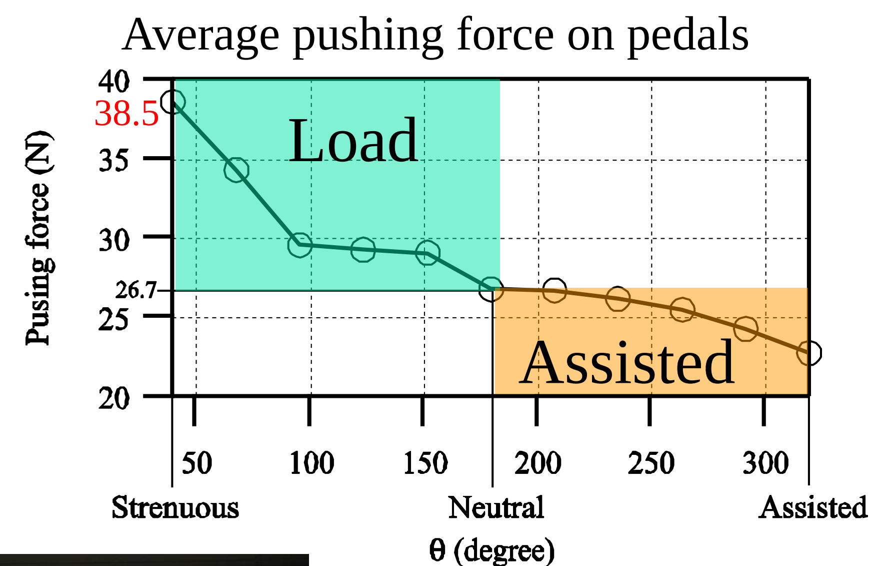
The above control law guarantees the stability of the closed-loop cart control system if there exists a common symmetric positive definite matrix *P* such that

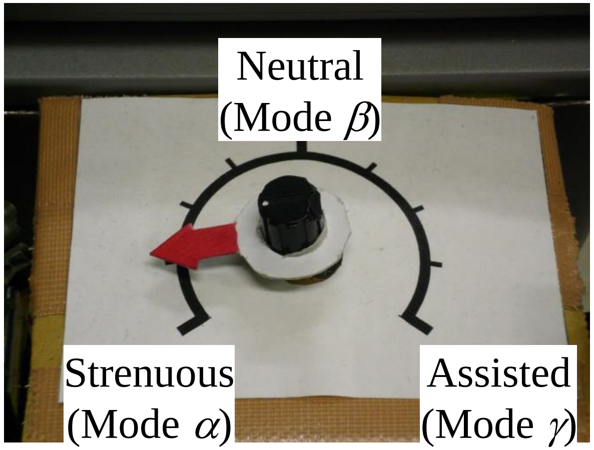
$$P\bar{A}_\alpha(\Gamma) + \bar{A}_\alpha^T(\Gamma)P < 0,$$
$$P\bar{A}_\beta(\Gamma) + \bar{A}_\beta^T(\Gamma)P < 0,$$
$$P\bar{A}_\gamma(\Gamma) + \bar{A}_\gamma^T(\Gamma)P < 0$$

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

Experimental Results (Flat Road)





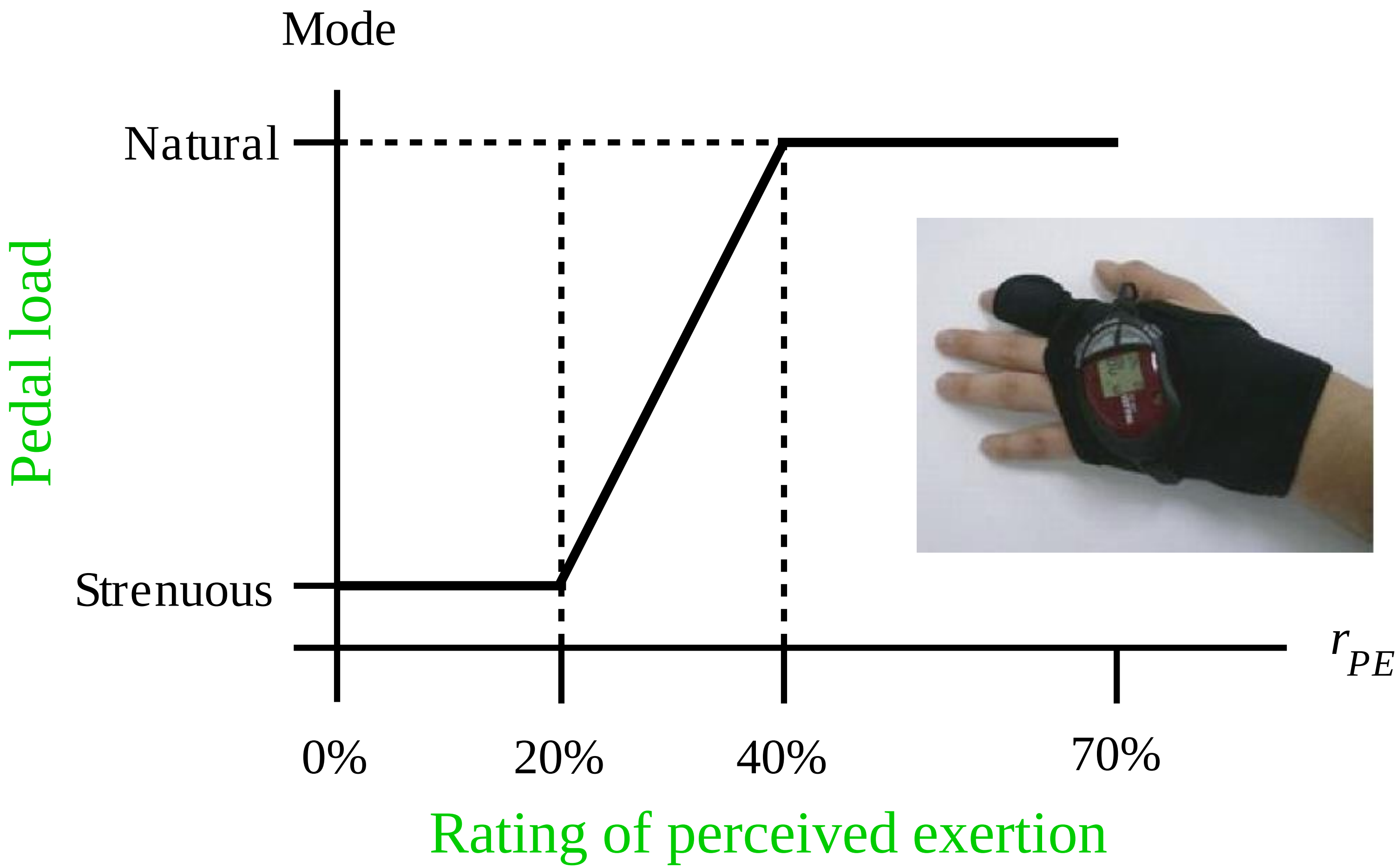


Controller Design

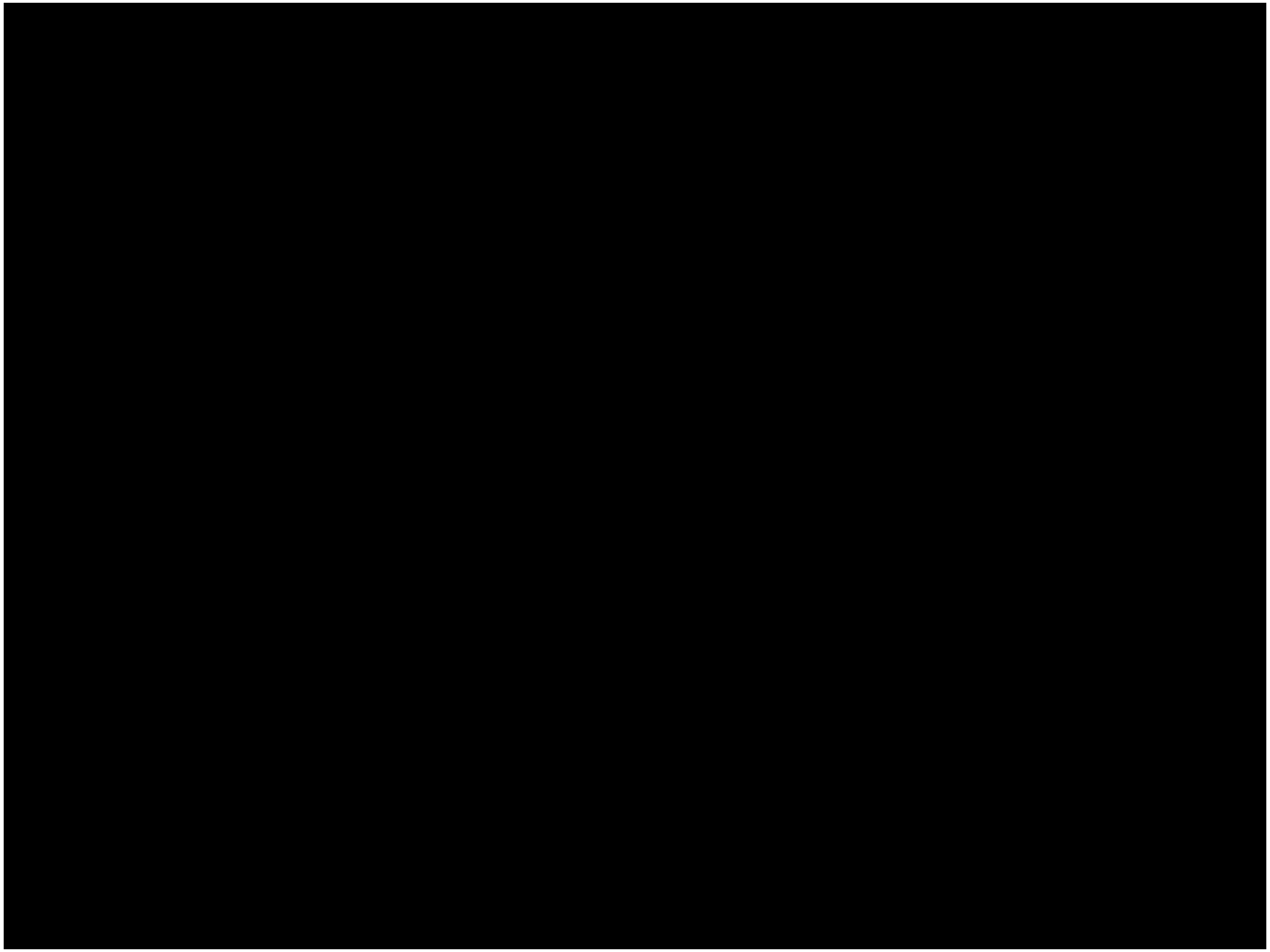
Step 3

Automatic selection of a load

Automatic Selection of Pedal Load



Experiments



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/Installation of knob/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.

Thank you