Motion Control of NXTway(LEGO Segway)
— Control Experiments with LEGO Mindstorms NXT —

Ryo Watanabe, Waseda University
1. Introduction
1. Introduction

• LEGO Mindstorms
  Integrated Development Environment for Educational Robot

- Programming Environment(GUI)
- Controller, Actuators, and Sensors
- LEGO Technic Parts
- RCX(1998-)
- NXT(2006-)

Educational Robots
1. Introduction

- Robots build with LEGO Mindstorms

- Steve Hassenplug’s Legway
  The most famous self-balancing robot built with LEGO Mindstorms

Dean Kamen’s Segway
1. Introduction

- NXTway-G (LEGO Segway with Gyro Sensor)

Discuss the possibility of LEGO Mindstorms NXT as the platform for Control Experiment.

- Modeling
- Model-based Controller Design
- Numerical Simulation
- Implementation of Control System
- Control Experiment
2. LEGO Mindstorms NXT
2. LEGO Mindstorms NXT

- Overview

LEGO Mindstorms NXT

NXT Block (CPU), Servo Motors, and Sensors

+ LEGO Technic Parts

Educational Robots
2. LEGO Mindstorms NXT

• NXT Block

Processors
- Main processor: Atmel 32-bit ARM processor, AT91SAM7S256
  256 KB FLASH, 64 KB RAM, 48 MHz
- Co-processor: Atmel 8-bit AVR processor, ATmega48
  4 KB FLASH, 512 Byte RAM, 8 MHz

Interface
- 4 input ports 6-wire interface
  supporting digital and analog interface
- 3 output ports 6-wire interface
  supporting input from encoders
- 4 button user-interface Rubber buttons

Communication
- Bluetooth wireless communication
  CSR BlueCoreTM 4 v2.0 +EDR System
- USB 2.0 communication Full speed port
  12 Mbit/s
2. LEGO Mindstorms NXT

- Programming Environment
  
  NXT-G(GUI), RoboLab(GUI), RobotC(C), NXC(C), leJOS(Java), …

IDE (Integrated Development Environment) for LEGO Mindstorms NXT developed by Carnegie Mellon University Robotics Academy

RobotC

Feature

- C Language
- Useful Debugger
- Floating-Point Calculation
- Timer Resolution: 1(ms)
3. NXTway-G
3. NXTway-G

- Legway and NXTway

  Dean Kamen’s Segway

  Measurement of light sensor

  Body’s rotation angle

  Information on wheel’s rotation angle is NOT used

  Internal Stability is NOT achieved
3. NXTway-G

- NXTway-G

Remote Control Interface

DC Motor

Rotary Encoder

Gyro Sensor

Motor Voltage

Angular Velocity (Body)

Rotation Angle (Wheel)
3. NXTway-G

- Dynamics of NXTway-G

- Linearized Model around Equilibrium Point

State Variable
\[
\theta = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}, \quad \omega = \begin{bmatrix} \omega_1 \\ \omega_2 \end{bmatrix}
\]

Equilibrium Point
\[
\theta = 0, \quad \omega = 0
\]

State Equation
\[
\frac{d}{dt} \begin{bmatrix} \omega \\ \theta \end{bmatrix} = \begin{bmatrix} -J_l^{-1}D_l & -J_l^{-1}K_l \\ I & 0 \end{bmatrix} \begin{bmatrix} \omega \\ \theta \end{bmatrix} + \begin{bmatrix} J_l^{-1}E_l \\ 0 \end{bmatrix} e_m
\]
4. Motion Control of NXTway-G
4. Motion Control of NXTway-G

- Structure of Control System

- Control Objective
  - Internal Stabilization
  - Position Tracking

- Control System
  - Reference Generator
  - Friction Compensator
  - Stabilization & Tracking Controller
  - Tuning Parameter

- NXTway-G
  - Motor Voltage
  - Angular Velocity (Body)
  - Rotation Angle (Wheel)
4. Motion Control of NXTway-G

- Stabilization & Tracking Controller

Tracking Performance
\[ \| G_{z_1/w_1} \|_\infty < 1 \]

Sensitivity of Control Input
\[ \| G_{z_2/w_1} \|_\infty < 1 \]

\[
K(s) = \begin{bmatrix} K_1(s) & K_2(s) \end{bmatrix}^T
\]

\[ K_1(s) \text{ (solid), } K_2(s) \text{ (dashed)} \]
4. Motion Control of NXTway-G

- Simulation Results

Internal Stability

Tracking

\[-8\text{(V)} \leq e_m \text{ (Motor Voltage)} \leq 8\text{(V)}\]
4. Motion Control of NXTway-G

- Experimental Results
  - Internal Stability
  - Tracking
  - Slope
  - Demonstration
4. Motion Control of NXTway-G

- Experimental Results

<table>
<thead>
<tr>
<th></th>
<th>Internal Stability</th>
<th>Tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment</strong></td>
<td><img src="image1" alt="Graphs showing internal stability" /></td>
<td><img src="image2" alt="Graphs showing tracking performance" /></td>
</tr>
<tr>
<td><strong>Simulation</strong></td>
<td><img src="image1" alt="Graphs showing internal stability" /></td>
<td><img src="image2" alt="Graphs showing tracking performance" /></td>
</tr>
</tbody>
</table>

- Offsets in angle responses
- Similar tracking performance
5. Conclusion
5. Conclusion

- In this presentation, we discussed …
  
  Design and Construction of NXTway-G
  NXTway-G’s Motion Control System

- From the experimental results, we see …
  
  The potential of LEGO Mindstorms NXT for the platform of control experiments
  The power of model-based control theory

- Next Project

NXT Motorbike