ANALOG AND LABVIEW-BASED CONTROL OF A MAGLEV SYSTEM WITH NI-ELVIS

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Outline of Presentation

- Objectives
- Background
- Maglev Testbed
- Control Strategies
- Simulation Studies
- Experimental Studies
- Summary
- Future Work
Objectives

Using a low cost maglev system for mechatronics education:

- Develop a linearized model
- Investigate classical linear controllers
- Implement controllers using analog circuits on NI-ELVIS
- “Implement” controllers using LabVIEW
- Compare performance of controllers
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What is Maglev?

- **Maglev** = Magnetic Levitation
- Levitate objects by electromagnetic forces to cancel effect of gravity
- Established technology:
  - high-speed maglev vehicles
  - maglev bearings
  - vibration isolation systems, etc.
Examples

**Maglev train** (China) (speeds of 430 km/h)

**Maglev Bearing**

**Maglev Brand Fans**

Maglev = Standard magnetic flux + Maglev flux

Maglev System

360° Maglev Rotation

standard magnetic flux

Maglev flux

**Maglev Law**

1. The Maglev system creates 360° attraction on the rotor, which results in stable rotation.
2. Maglev flux acts perpendicular to the standard magnetic flux.
Control Strategies

- **Linear Control**
  - Classical PID
  - PID with gain scheduling
  - Phase-lead, Phase-lag
  - LQR, LQE, LQG, $H_\infty$, $\mu$-synthesis

- **Nonlinear Control**
  - On-off
  - PWM
  - Fuzzy-logic
  - Neural-network control
  - Feedback linearization
  - Adaptive control
  - Backstepping theory
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Physical Testbed
Testbed Pictorial

Electromagnet (Actuator)

IR Emitter (Sensor)

IR Detector (Sensor)

Controller  Power Supply
Infrared (IR) Sensor

- Infrared emitter and detector pair
- Acts as a variable resistor
- Levitated object blocks path, changes light intensity
- Linear behavior in operating region

\[ \nu_s = \beta x \]
Sensor and Controls Logic

- The emitter generates constant light intensity.
- The detector signal is amplified and compared with a reference voltage.
- Difference of signals used to adjust current to electromagnet.
  - If the levitated object is too close to electromagnet (detected IR signal too small), the current is reduced.
  - If the levitated object is too far (detected IR signal too large), the current is increased.
Actuator

- Actuator is electromagnetic coil with steel bolt core
- Electromagnet obtained commercially
- FEA performed to check for magnetic saturation
- Power supply: 18 V / 3 A
Thermistor mounted to coil used to measure temperature during levitation.

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Nonlinear Model

\[ f(x, i, t) = -\frac{i(t)^2}{2} \frac{dL(x)}{dx} \]

\[ L(x) = L_1 + \frac{L_o x_o}{x} \]

\[ f(x, i, t) = \frac{L_o x_o}{2} \left( \frac{i(t)}{x(t)} \right)^2 = C \left( \frac{i(t)}{x(t)} \right)^2 \]

\[ m \frac{d^2 x(t)}{dt^2} = mg - f(x, i, t) \]

\[ m \frac{d^2 x(t)}{dt^2} = mg - C \left( \frac{i(t)}{x(t)} \right)^2 \]
Linearized Model

\[ f(x, i, t) = C\left(\frac{i_o}{x_o}\right)^2 + \left(\frac{2Ci_o}{x_o^2}\right)i(t) - \left(\frac{2Ci_o^2}{x_o^3}\right)x(t) + \ldots \]

\[ f(x, i, t) = f_o + f_1 + \ldots \]

\[ f_o(x, i) = C\left(\frac{i_o}{x_o}\right)^2 = mg \]

\[ f_1(x, i, t) = \left(\frac{2Ci_o}{x_o^2}\right)i(t) - \left(\frac{2Ci_o^2}{x_o^3}\right)x(t) \]

\[ m\frac{d^2x(t)}{dt^2} = mg - f \]

\[ m\frac{d^2x(t)}{dt^2} = mg - f_o - \left(\frac{2Ci_o}{x_o^2}\right)i(t) + \left(\frac{2Ci_o^2}{x_o^3}\right)x(t) \]
Linearized Model (cont’d)

\[ f_o = C \left( \frac{i_o}{x_o} \right)^2 = mg \]

\[ m \frac{d^2 x(t)}{dt^2} = -\left( \frac{2Ci_o}{x_o^2} \right) i(t) + \left( \frac{2Ci_o^2}{x_o^3} \right) x(t) \]

\[ ms^2 X(s) = -\left( \frac{2Ci_o}{x_o^2} \right) I(s) + \left( \frac{2Ci_o^2}{x_o^3} \right) X(s) \]

\[
G(s) = \frac{X(s)}{I(s)} = \frac{-\left( \frac{2Ci_o}{x_o^2} \right)}{ms^2 - \left( \frac{2Ci_o^2}{x_o^3} \right)} = \frac{-\left( \frac{2Ci_o}{mx_o^2} \right)}{s^2 - \left( \frac{2Ci_o^2}{mx_o^3} \right)}
\]
Block Diagram

\[
G(s) = \frac{X(s)}{I(s)} = -\frac{\left(\frac{2Ci_o}{x_o^2}\right)}{s^2m - \left(\frac{2Ci_o^2}{x_o^3}\right)} = -\frac{\left(\frac{2Ci_o}{mx_o^2}\right)}{s^2 - \left(\frac{2Ci_o^2}{mx_o^3}\right)}
\]
The electromagnet represented as a series combination of a resistor and inductor

Consider sensor output as the system output

Consider voltage to the electromagnet as the system input

\[ v(x, i, t) = Ri(t) + L(x) \frac{di(t)}{dt} \]

\[ G_o(s) = \frac{V_s(s)}{V(s)} = \frac{-2\beta Ci_o}{mLx_o^2} \left( s + \frac{R}{L} \right) \left( s^2 - \frac{2Ci_o^2}{mx_o^3} \right) \]
Block Diagram II

\[ G_o(s) = \frac{V_s(s)}{V(s)} = \frac{-2\beta C_i}{mLx_o^2} \left( s + \frac{R}{L} \right) \left( s - \frac{2C_i^2}{mx_o^3} \right) \]
The root-locus has a pole in the right-half plane; the system is unstable.

\[ G_o(s) = \frac{824000}{(s + 232)(s + 49.5)(s - 49.5)} \]
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Control Block Diagram

- Error signal calculated as difference of setpoint and sensor output
- Error signal is input to controller
- Bias is added to controller output, amplified, and input to “maglev plant”
- Controlled output is actual output
Control Strategies

- **Proportional Control**
  - Controller output is proportional to error
  
  \[ G_p(s) = K_P \]

- **Lead-Lag Control**
  - Adds a zero and a pole to the open-loop system

\[
G_{Lead/Lag}(s) = K \frac{s + z}{s + p} 
\]

- **Lead** for \(0 < z < p\)
- **Lag** for \(0 < p < z\)
Control Strategies

- **PD Control**
  - Adds derivative term
  
  \[ G_{PD}(s) = K_P + K_D s \]

- **PID Control**
  - Integral term makes steady-state error zero
  
  \[ G_{PID}(s) = K_P + K_D s + \frac{K_I}{s} \]
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Proportional Controller acts as a gain; cannot move poles into left-half plane.

Proportional Controller by itself cannot stabilize open-loop unstable system.
Lag Compensator

Lag Compensator cannot move poles into left-half plane

Lag Compensator by itself cannot stabilize an open-loop unstable system
Lead Compensator

Lead Compensator moves poles into left-half plane

Lead Compensator can stabilize open-loop unstable system

Gain Margin: 13.2 dB
Phase Margin: 15.8 deg
Lead Compensator Response

**Step Response**
Settling Time: 0.157s  
Steady-State Error: 0.24

(Zero at -100 rad/s, Pole at -1000 rad/s)

**Impulse Response**
Settling Time: 0.164s
PD Controller

PD Controller moves poles into left-half plane

PD Controller can stabilize open-loop unstable system

Gain Margin: 2.61 dB
Phase Margin: 7.28 deg
PI Controller cannot stabilize open-loop unstable system.
PID Controller

PID Controller moves poles into left-half plane

PID Controller can stabilize open-loop unstable system

Gain Margin: 3.42 dB
Phase Margin: 8.94 deg
**PID Controller Response**

**Step Response**
Settling Time: 0.354s
Steady-State Error: 0

\(K_p = 0.68, K_i = 3.12, K_d = 0.0141\)

**Impulse Response**
Settling Time: 0.172s
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Maglev Experimental Station

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NI-ELVIS

National Instruments’ Educational Laboratory Virtual Instrumentation Suite
National Instruments’ Educational Laboratory Virtual Instrumentation Suite
Analog Control with NI-ELVIS

Mechatronics Laboratory, Marquette University, Oct 27, 2005
$G(s) = \frac{V_D}{V_{sensor}} = \frac{s + \frac{1}{R_5 C_1}}{s + \frac{R_5 + R_6}{R_5 R_6 C_1}}$
Lead Compensator Analog Implementation

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PD Analog Circuit

\[ G(s) = \frac{V_{control}(s)}{V_{error}(s)} = \left( \frac{RP2}{RP1} \right) + \left( \frac{RD \times CD}{KD} \right)s \]
PD Analog Circuit Implementation

Sensor → Sensor Output → Difference → Proportional → Summation → Controller Output

Error → Derivative

K_p=0.68, K_D=0.0141
PID Analog Circuit

\[
G(s) = \frac{V_{\text{control}}(s)}{V_{\text{error}}(s)} = \left(\frac{RP2}{RP1}\right)K_p + \left(\frac{1}{RI \times CI}\right)K_i + \left(\frac{RD \times CD}{K_D}\right)s
\]

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PID Analog Circuit Implementation

Setpoint

Sensor Output

Difference

Error

Proportional

Summation

Integral

Derivative

Bias

Bias

Setpoint for Antiwindup

Output

KP = 0.68, KI = 3.12, KD = 0.0141

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Analog Implementation
LabVIEW-based Control

15V
IR Diode
RS 276-143
R1 150 Ohm 25W

15V
IR Photo Transistor
RS 276-145

15V
LabVIEW - Maglev.VI
DAC 0
ACH 2
R2 33k
R3 12k

18V
Coil
D4 1N5400
Q2 2N3055
R33 180
D4

18V

0

18V

0

0

0
LabVIEW VI Program

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Levitation of AA Battery
Levitation of Thin Ring
Levitation of Nested Washer

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Levitation of 9V Battery

Mechatronics Laboratory, Marquette University, Oct 27, 2005
Levitation of Various Objects
Levitation of Various Objects
## Current Comparisons

<table>
<thead>
<tr>
<th>OBJECT</th>
<th>MASS (g)</th>
<th>% Variation From 6.8g</th>
<th>CURRENT (A)</th>
<th>A - Lead</th>
<th>A - PD</th>
<th>A - PID</th>
<th>LV - PD</th>
<th>LV - PID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nested Washer</td>
<td>8.94</td>
<td>29.75%</td>
<td>1.34</td>
<td>1.49</td>
<td>1.47</td>
<td>1.49</td>
<td>1.46</td>
<td></td>
</tr>
<tr>
<td>Bolt</td>
<td>10.64</td>
<td>54.43%</td>
<td>1.29</td>
<td>1.36</td>
<td>1.32</td>
<td>1.39</td>
<td>1.37</td>
<td></td>
</tr>
<tr>
<td>Bolt 2</td>
<td>14.23</td>
<td>106.53%</td>
<td>1.59</td>
<td>1.68</td>
<td>1.60</td>
<td>1.72</td>
<td>1.72</td>
<td></td>
</tr>
<tr>
<td>AA Battery</td>
<td>18.89</td>
<td>174.17%</td>
<td>1.16</td>
<td>1.29</td>
<td>1.24</td>
<td>1.30</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td>Thin Ring</td>
<td>23.49</td>
<td>240.93%</td>
<td>1.27</td>
<td>1.36</td>
<td>1.34</td>
<td>1.37</td>
<td>1.26</td>
<td></td>
</tr>
<tr>
<td>Splined Ring</td>
<td>44.27</td>
<td>542.53%</td>
<td>N/A</td>
<td>1.78</td>
<td>1.79</td>
<td>N/A</td>
<td>1.75</td>
<td></td>
</tr>
<tr>
<td>9-Volt Battery</td>
<td>47.36</td>
<td>587.37%</td>
<td>N/A</td>
<td>N/A</td>
<td>2.19</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Large Bolt</td>
<td>50.95</td>
<td>639.48%</td>
<td>N/A</td>
<td>N/A</td>
<td>2.27</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>
Addition of Second Coil
Stiffness

The graph shows the relationship between force (N) and displacement (m) for different balls. The curve is represented by the equation $135000x^2$. The displacement values range from $0.0$ to $2.5 \times 10^{-4}$ m, and the force values range from $0.0$ to $7.0 \times 10^{-3}$ N.
PD Controller Response

![Graph showing PD Controller Response](image)

- **Analog PD**
- **LabVIEW PD**

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Summary

- Developed nonlinear and linearized model
- Conducted simulation studies to compare controllers and select gains
- Implemented PID-type controllers using analog circuits with NI-ELVIS board
- Developed software-based controllers using LabVIEW
- Compared "hardware" vs. "software" based controllers
- Added second coil for determining stiffness and system response
- Tested practical differentiator and anti-windup circuits
Closing

- Applied classical linear control strategies to a linearized model of a nonlinear system
- Implemented analog controllers using NI-ELVIS
- Developed LabVIEW controllers
  - Can dynamically change controller type and parameters and observe effect on system in real-time
Outline of Presentation

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- Simulation Results
- Experimental Results
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  - Future Work
Future Work

- Implement nonlinear and optimal control strategies in LabVIEW & compare performance with linear control strategies.
- Develop a detailed FEA model to optimize the shape of the electromagnet for maximum field strength.
- Design an array of sensors to translate levitated object vertically.
- Add horizontal electromagnets for two degree-of-freedom system.
Future Work (cont’d)

- Add velocity sensor for controlled damping
- Develop more advanced model
  - Include gyro-dynamics
  - Include skin friction using a CFD model
- Test remote access to VI through internet
- Create a virtual reality model using Virtual Reality Toolbox
  - Visualization of simulation without actual implementation
Questions ...
Movie of Levitated Ball
Magnetic Field FEA Results

Using FEMM package
A pole needs to be added to differentiator circuit for “roll-off” of high frequency response.

Without additional pole, differentiator circuit just amplifies any high frequency noise signals.

Need to filter high frequency signals from signal going to the differentiator.

Capacitor, CN, added in the differentiator circuit

\[
\frac{V_{out}(s)}{V_{in}(s)} = \frac{(RD)s}{(RD \times CN)s + 1}
\]
Anti-windup Circuit

- The integral circuit integrates the error with respect to time.
- If error is large & constant, e.g., when the object is not present, integral action will continuously increase until saturation.
- Need an “anti-windup” circuit.
<table>
<thead>
<tr>
<th>SYMBOL</th>
<th>DESCRIPTION</th>
<th>SI UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$</td>
<td>Mass of the object</td>
<td>kg</td>
</tr>
<tr>
<td>$x_o$</td>
<td>Equilibrium distance</td>
<td>m</td>
</tr>
<tr>
<td>$V_{in}$</td>
<td>Voltage supplied to electromagnet</td>
<td>V</td>
</tr>
<tr>
<td>$i_o$</td>
<td>Equilibrium current</td>
<td>A</td>
</tr>
<tr>
<td>$C$</td>
<td>Force constant</td>
<td>N-m²/A²</td>
</tr>
<tr>
<td>$R$</td>
<td>Coil resistance</td>
<td>Ω</td>
</tr>
<tr>
<td>$L$</td>
<td>Coil inductance</td>
<td>H</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Sensor gain</td>
<td>V/m</td>
</tr>
<tr>
<td>$\beta_F$</td>
<td>Transistor constant</td>
<td></td>
</tr>
</tbody>
</table>
SISO Design Tool

SISO Design Tool

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PD Controller Response

**Step Response**
Settling Time: 0.157s
Steady-State Error: 2.15

\((K_p=0.68, \ K_D=0.0141)\)

**Impulse Response**
Settling Time: 0.562s

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PID Controller Response

[Graph showing the response of an analog PID controller versus a LabVIEW PID controller over time and sensor output voltage.]
Margin Plots for PD Controller

- Phase Margin (degrees) vs. Controller Gain
- Gain Margin (dB) vs. Controller Gain
Margin Plots for PID Controller

[Graph showing Phase Margin (degrees) vs Controller Gain]

[Graph showing Gain Margin (dB) vs Controller Gain]