AI-based Low Computational Power Actuator/Sensor Fault Detection Applied on a MAGLEV Suspension

K. Michail, K. Deliparaschos, A. Zolotas, S. G. Tzafestas

21st Mediterranean Conference on Control and Automation
Crete, Greece, 25-28 June 2013
CONTENTS

- Introduction
- The proposed sensor fault detection scheme
- Training the fault detection unit
- The case study: A maglev suspension
- Simulations
- Conclusions
A Typical System

propose FTC scheme for sensor fault detection with low computational cost
Sensor/actuator signals estimation

Actuators (Driving Signals) → $\mathcal{U}$ → Est.₁ → $\hat{y}_1$ → Estimated Driving signals

Sensors (Measurements) → $\gamma$ → Typical bank of estimators for sensor FD → $\hat{y}_2$ → $\hat{y}_{n_y}$ → Estimated measurements

Est.₂ → $\hat{u}_1$ → iFD unit (NN-based)

Est.ₙ → $\hat{u}_2$ → $\hat{u}_{n_u}$
Proposed Fault Tolerant Scheme
CONTENTS

- Introduction
- The proposed sensor fault detection scheme
- Training the fault detection unit
- The case study: A maglev suspension
- Simulations
- Conclusions
Neural Network:
Training data set of the iFD

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Measured signals</th>
<th>Estimated signals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy Set</td>
<td>$y_1$, $y_2$, $y_3$, $y_4$, $u$</td>
<td>$\hat{y}_1$, $\hat{y}_2$, $\hat{y}_3$, $\hat{y}_4$, $u$</td>
</tr>
<tr>
<td>Healthy Set</td>
<td>$D^1_{y_1}$, $D^1_{y_2}$, $D^1_{y_3}$, $D^1_{y_4}$, $D^1_{u_{y_1,y_2,y_3,y_4}}$</td>
<td>$D^1_{\hat{y}<em>1}$, $D^1</em>{\hat{y}<em>2}$, $D^1</em>{\hat{y}<em>3}$, $D^1</em>{\hat{y}<em>4}$, $D^1</em>{u_{\hat{y}_1,y_2,y_3,y_4}}$</td>
</tr>
<tr>
<td>Faulty Set</td>
<td>$c_1$, $D^3_{y_2}$, $c_1$, $D^3_{y_4}$, $D^3_{u_{y_2,y_4}}$</td>
<td>$c_1$, $c_1$, $D^3_{y_4}$</td>
</tr>
<tr>
<td>Faulty Set</td>
<td>$c_1$, $D^4_{y_2}$, $c_1$, $c_1$, $D^4_{u_{y_2}}$</td>
<td>$c_1$, $c_1$, $c_1$, $c_1$</td>
</tr>
</tbody>
</table>
Neural Network architecture
CONTENTS

➢ Introduction

➢ The proposed sensor fault detection scheme

➢ Training the fault detection unit

➢ The case study: A maglev suspension

➢ Simulations

➢ Conclusions
The test case: Maglev System

EMS serves two purposes:
- Support the vehicle and passengers
- Ensure proper ride quality
Aim: Maintain the Control performance within limits under deterministic and stochastic disturbances while ensuring the control performance in the presence of sensor faults.

<table>
<thead>
<tr>
<th>Maximum control effort, $u_{cp}$</th>
<th>$\leq 300v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Settling time, $t_s$</td>
<td>$\leq 3s$</td>
</tr>
<tr>
<td>Airgap steady state error, $e(z_i-z)_{ss}$</td>
<td>$= 0$</td>
</tr>
</tbody>
</table>
A FTC scheme for sensor fault detection of the EMS

Sensor Fault Accommodation Recovery
1. Single or Multiple Sensor Occurs
2. Fault is Detected
3. Faulty sensor/s Isolation
4. Controller Reconfiguration
Sensor Fault Modelling

Multiplicative

Additive

Fault Categories

Fault Types

\[ y_o = f \times y_i \]

\[ f \rightarrow \times \rightarrow y_o \]

\[ y_i \rightarrow \times \rightarrow y_o \]

Multiplicative

\[ y_o = f + y_i \]

\[ f \rightarrow + \rightarrow y_o \]

Additive

Abrupt

Incipient

Indeterminate

Current fault profile

Faulty current measurement

Faulty-free current measurement

Current - A

Time - sec

Faulty current measurement

Faulty-free current measurement

Current - A

Time - sec

x5
Sensor Fault Scenaria

- Abrupt faults; additive faults the normal sensor’s output value superimposed with a low frequency random signal and multiplicative faults result to sensors’ output 5 times larger than normal.

- 4 sensors in the maglev sensor set; assuming only 3 can fail i.e current i, vertical velocity and the vertical acceleration.

- Both the abrupt/multiplicative and abrupt/additive sensor fault profiles are used for each sensor,

- Subsequent faults can happen with a time difference of about 1 second.
CONTENTS

- Introduction

- The proposed sensor fault detection scheme

- Training the fault detection unit

- The case study: A maglev suspension

- Simulations

- Conclusions
Simulation results

<table>
<thead>
<tr>
<th>id</th>
<th>Faulty sensor(s)</th>
<th>Mu.</th>
<th>FA</th>
<th>Ad.</th>
<th>FA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>St.</td>
<td>St.</td>
<td>St.</td>
<td>St.</td>
</tr>
<tr>
<td>1</td>
<td>No fault</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>(i)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>(\dot{z})</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>(\ddot{z})</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>5</td>
<td>(i \rightarrow \dot{z})</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>6</td>
<td>(i \rightarrow \ddot{z})</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>7</td>
<td>(\dot{z} \rightarrow \ddot{z})</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>8</td>
<td>(\dot{z} \rightarrow \ddot{z} \rightarrow i)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Mu. – Multiplicative faults
Ad. – Additive faults
FA – False alarms
St. – Stochastic response
Dt. – Deterministic response

MED’13 Control Conference
Crete, Greece
Sensor Fault Sequence

\[ \ddot{z} \rightarrow \dot{z} \rightarrow i \]

- Fault free
- Accel. Fault
- vel. Fault
- vel. Fault

Air gap with acceleration Fault

- Airgap signal with fault free conditions
- Airgap under fault scenario with id: 8

Current Residual

- Current residual
- Current Threshold

Fault Time

MED’13 Control Conference
Crete, Greece
Binary Switch state

From Decision making unit $I_S i \rightarrow y_i \rightarrow y_{BS_i}$

MED’13 Control Conference
Crete, Greece
A comparison

A bank of Kalman estimators have been compared with the iFD unit. The results show that the iFD unit is about 10 times faster than the bank of Kalman filters.
CONTENTS

- Introduction
- The proposed sensor fault detection scheme
- Training the fault detection unit
- The case study: A maglev suspension
- Simulations
- Conclusions

MED’13 Control Conference
Crete, Greece
Conclusions & Discussion

- A fault detection mechanism is proposed aimed to minimise the computational cost.

- The proposed iFD is applied to a MAGLEV system example.

- The simulation results show promising results.

- Potential in FPGA implementation
AI-based Low Computational Power Actuator/Sensor Fault Detection Applied on a MAGLEV Suspension

K. Michail, K. Deliparaschos, A. Zolotas, S. G. Tzafestas

A. Zolotas acknowledges Univ of Sussex for travel grant support