

DELAY ESTIMATION FOR NETWORKED CONTROL SYSTEMS

by

WUTTICHAIR PRIRUNGRUANG

Submitted in partial fulfillment of the requirements

For the degree of Master of Science

Thesis Adviser: Dr. Stephen Phillips

Department of Electrical Engineering and Computer Science

CASE WESTERN RESERVE UNIVERSITY

January, 2003

To: *my parents, my country and mankind*

Table of Content

Chapter 1: Introduction

<i>Control Systems and Networks</i>	1
<i>Thesis Organization</i>	4

Chapter 2: Background

State Space Model for System with Delays

<i>Delay Less Than One Sampling Period</i>	5
--	---

<i>Longer Time Delay</i>	6
--------------------------------	---

Compensation for Network-Induced Delay

<i>Full-State Feedback</i>	7
----------------------------------	---

<i>Output Feedback</i>	8
------------------------------	---

Delay Modeling

<i>Constant Delay</i>	10
-----------------------------	----

<i>Random Delay</i>	11
---------------------------	----

<i>Markov Delay</i>	12
---------------------------	----

<i>Sensor-to-Controller Delay VS Sensor-to-Actuator Delay</i>	15
---	----

Chapter 3: Network Induced Delays and Compensations

<i>Introduction</i>	18
---------------------------	----

<i>Static Delay Compensation & Dynamic Delay Compensation</i>	21
---	----

<i>Offline Experiments</i>	26
----------------------------------	----

<i>Scenarios</i>	28
------------------------	----

<i>Real-time Experiments</i>	39
<i>Clock Synchronization</i>	40
<i>Set-up</i>	40
<i>Results and Discussion</i>	41
<i>Step Input</i>	41
<i>Sinusoidal Input</i>	44
<i>Effect of Design</i>	47
Chapter 4: Summary	52
Appendices	53
References	66

List of Figures

Figures	Page
Figure 2.1 Plant and estimator for full state feed back	8
Figure 2.2 Plant and estimator diagram with output feedback	9
Figure 2.3 Network delays under the construction constraints in [6] when there is no queuing	10
Figure 2.4 Delays of the CAN network in [6] when sent messages have different priority	11
Figure 2.5 Markov Delay Model	13
Figure 2.6 Simulated delays histogram according to the state of the Markov chain when the load is low, l , and high, h	14
Figure 2.7 The Markov delay of tow network loads – Low and High with $Q_{LL} = 0.85$, $Q_{LH} = 0.15$, $Q_{HL} = 0.35$ and $Q_{HH} = 0.65$	14
Figure 2.8 (a) Delay measurements (b) Probabilistic distribution functions of τ_{sc} and τ_{ca} in [6] of CAN	15
Figure 2.9 Delays measurement on Ethernet with low network load in [6]	16
Figure 2.10 Network delay measured from Ethernet with an extra load as set in [6]	17
Figure 2.11 Delay measurements of Ethernet as setup in [6] in high-load environment	17
Figure 3.1 NCSs schematic with measurable and immeasurable delays	18
Figure 3.2 Timing diagram of a delayed system	20
Figure 3.3 Timing diagram for the algorithms	22
Figure 3.4 Flow chart of the algorithm (a) SDE and (b) DDE	24
Figure 3.5 n -point tableau	25
Figure 3.6 Network diagram describes in the first scenario	28
Figure 3.7 Arrays of created delay under the first scenario constraints	29
Figure 3.8 Step responses showing effect of τ_{sc} compensation	29
Figure 3.9 Responses of τ_{sc} -and- τ_{ca} compensated system ($\tau_{sc} = 0.08$ sec and $\tau_{ca} = 0.08$ sec)	30
Figure 3.10 Control signals of the double-integrator system when <i>i</i>) only compensated for τ_{sc} (Figure 3.8) <i>ii</i>) compensated for both τ_{sc} and τ_{ca} (Figure 3.9)	30
Figure 3.11 Network diagram for the second scenario	31
Figure 3.12 Emulated network-induced delay under the second scenario	32
Figure 3.13 Step responses of the system from the second scenario when both delays were compensated for and when only τ_{sc} was compensated for	32
Figure 3.14 Emulated network-induced delay under the second scenario	33
Figure 3.15 Desired response and response of the full-compensated system (using SDE to estimate the delay in Figure 3.14)	33
Figure 3.16 Network diagram of the third scenario	34
Figure 3.17a CWRUNet delays measured in [11]	35

Figure 3.17b Histogram of CWRUNet delays measured in [11]	35
Figure 3.18 Step response of the system using SDE as the algorithm of estimation where mean of the delay ($\bar{\tau}_{ca} = 0.0185$ sec) was the compensation value	36
Figure 3.19 Step response of the system using SDE as the algorithm of estimation where mode of the delay ($\bar{\tau}_{ca} = 0.0060$ sec) was the compensation value	36
Figure 3.20 Responses of the system employing DDE as the algorithm	37
Figure 3.21 Difference of the two responses of Figure 3.20	38
Figure 3.22 Step responses of fully compensated system when <i>i)</i> $\tau_{ca,n}$ compensated by $\tau_{ca,n-1}$ <i>ii)</i> $\tau_{ca,n}$ compensated by $\tau_{sc,n}$	39
Figure 3.23 Comparison between the two approaches with no delays response	39
Figure 3.24 Network diagram of the experiment	41
Figure 3.25 Logical diagram of the experiment	41
Figure 3.26 Step response from the experiment	42
Figure 3.27 Step response, delay and interpolation of the delay of the system	42
Figure 3.28 Step response of the adjusted-estimation system	43
Figure 3.29 Fifty-point tableau and twenty-point tableau of the double integrator system in the experiment	44
Figure 3.30 Output of the compensated double integrator with sinusoidal signal as the reference input	45
Figure 3.31 Error between input and output of the system in Figure 3.30	45
Figure 3.32 Output of the compensated double integrator system in non-deterministic delay environment	46
Figure 3.33 Error between input and output of the system in Figure 3.32	46
Figure 3.34 Step responses of the system where the closed-loop poles are $z = 0.6249 \pm j0.3781$	47
Figure 3.35 Step responses of the system where the closed-loop poles located at $z = 0.5716 \pm j0.3131$	48
Figure 3.36 Step responses of the system where the closed-loop poles located at $z = 0.4860 \pm j0.2941$	49
Figure 3.37 Step responses of the system where the closed-loop poles located at $z = 0.4710 \pm j0.2850$	49
Figure 3.38 Bounded and unbounded regions of the double integrator system when <i>i)</i> uncompensated system <i>ii)</i> τ_{sc} – compensated system <i>iii)</i> fully compensated system	51

Delay Estimation for Networked Control Systems

Abstract

by

WUTTICHAIR PRIRUNGRUANG

It is known that transmission delays affect the dynamics of feedback control systems. Therefore, system designers should be aware of and compensate for the delays to prevent degradation. However, when dealing with real-time networked control systems measuring real-time transmission delay (e.g. delay between sensor and actuator) is not always possible. The alternative is to estimate the delay from available information, which can allow recovery of the desired dynamics.

Two estimation approaches are proposed in this study, static delay estimation and dynamic delay estimation. Static delay estimation is suitable for networks with consistent delays or varying delays with known patterns. Dynamic delay estimation is proposed for systems with unknown delay patterns, such as control systems over Ethernet.

