ERROR HANDLING AND CONTROLLER DESIGN FOR CONTROLLER AREA NETWORK-BASED NETWORKED CONTROL SYSTEM

MOHD BADRIL BIN NOR SHAH

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To my dearest mother, Rahmah Nasri for her compassion and prayer.

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ABSTRACT

Networked Control System (NCS) is a feedback control system which dynamic process is running via the communication channel. Surrounded by many choices of network types that can be used to establish an NCS, Controller Area Network (CAN) is a popular choice widely used in most real-time applications. Under harsh environment, fault at transmission line for CAN-based NCS is more prominent compared to fault in network nodes. Fault in bus line of CAN will induce data error which will result in data dropout or/and time delay which consequently lead to performance degradation or system instability. In this thesis, strategies to handle fault occurrence in CAN bus are proposed in order to properly analyse the effect of fault to CAN-based NCS performance. To implement the strategies, first, fault occurrences are modelled based on fault inter-arrival time, fault bursts duration and Poisson law. By using fault and message attributes, Response Time Analysis (RTA) is performed and the probability of NCS message that misses its deadline is calculated based on Homogeneous Poisson Process (HPP). A new error handling algorithm per-sample-error-counter (PSeC) is introduced to replace native error handling of CAN. PSeC mechanism is designed based on online monitoring and counting of erroneous sensor and control signal data at every sampling instance and it gives a bound parameters known as Maximum Allowable Number of Data Retransmission (MADR). If the number of retransmission for NCS message violates the value of MADR, the data will be discarded. With the utilization of PSeC mechanism to replace the Native Error Handling (NEH) of CAN, the probability of NCS message that misses its deadline can be translated to the probability of data dropout of NCS message. Despite the PSeC has prevented network from congestion which can lead to prolonged loop delay, it also introduces one-step loop delay and data dropout. Therefore, the controller that is able to compensate the effect of delay and data dropout should be introduced. Thus, a control algorithm is designed based on Lyapunov stability theory formulated in Linear Matrix Inequality (LMI) form by taking into account network delay and data dropout probability. In order to proof the efficacy of the strategies, Steer-by-Wire (SbW) system is used and simulated in TrueTime MATLAB®/Simulink environment. Simulation results show that the strategies of introducing PSeC mechanism and the designed controller in this work have superior performance than NEH mechanism for CAN-based NCS environment in terms of integral of the absolute error (IAE) and energy consumption.

ABSTRAK

Sistem Pengawal Rangkaian (NCS) adalah sistem kawalan suapbalik di mana proses dinamiknya berfungsi melalui saluran telekomunikasi. Dengan pelbagai pilihan jenis rangkaian yang boleh diguna untuk membentuk sebuah NCS, Rangkaian Pengawalan Kawasan (CAN) adalah pilihan popular yang telah digunakan secara meluas dalam kebanyakan aplikasi masa sebenar. Dalam keadaan getir, kerosakan talian CAN akan menyebabkan ralat data yang menyebabkan keciciran data dan lengah masa seterusnya menyebabkan kemerosotan prestasi atau ketidakstabilan pada sistem. Dalam tesis ini, strategi untuk mengendalikan kerosakan dalam CAN telah dicadangkan untuk menganalisa secara wajar kesan kegagalan pada NCS berasaskan CAN. Untuk melaksanakan strategi ini, kerosakan dimodel berdasarkan masa tiba kerosakan, tempoh ledakan kerosakan dan hukum Poisson. Dengan menggunakan sifat mesej dan kerosakan, Analisa Masa Tindak Balas (RTA) dilakukan dan kebarangkalian mesej NCS terlepas batas waktu boleh dikira menggunakan sifat Proses Homogen Poisson (HPP). Satu algoritma baru yang iaitu pembilang-ralat-setiap-sampel (PSeC) telah diperkenalkan untuk menggantikan Pengendali Ralat Natif (NEH) untuk CAN. Mekanisme PSeC ini direka berdasarkan pemantauan atas talian dan pengiraan ralat data penderia dan isyarat pengawal pada setiap sampel, juga memberikan satu parameter dikenali sebagai Bilangan Maksimum Penghantaran Semula Data (MADR). Jika bilangan penghantaran data melebihi nilai MADR, data tersebut akan dicicirkan. Dengan penggunaaan mekanisme PSeC untuk menggantikan NEH pada CAN, kebarangkalian mesej NCS terlepas batas waktu boleh diterjemahkan kepada kebarangkalian keciciran data NCS. Walaupun mekanisme PSeC telah mengelakkan dari berlakunya kesesakan talian, ia juga telah menghasilkan satu-langkah lengah masa gelung dan keciciran data. Maka, satu pengawal yang boleh menampung kesan lengah masa gelung dan keciciran data hendaklah direka. Dengan itu, satu algoritma pengawal direka berdasarkan sifat Lyapunov diformulasikan dalam Ketidaksamaan Matriks Linear (LMI) dengan mengambil kira lengah rangkaian dan kebarangkalian keciciran data. Untuk mengesahkan keberkesanan strategi yang dicadangkan, sistem Kemudi Menggunakan Wayar (SbW) telah diguna dan disimulasi dalam persekiratan TrueTime berasaskan MATLAB®/Simulink. Keputusan simulasi menunjukkan strategi menggunakan mekanime PSeC dan pengawal yang telah direka itu menunjukkan keunggulan prestasi berbanding mekanisme NEH dalam persekitaran NCS yang berasaskan CAN dari segi kamiran ralat mutlak (IAE) dan penggunaan tenaga.

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LIST OF ABBREVIATIONS

ARQ – Automatic Retransmission Request
BbW – Brake-by-Wire
BDS – Bernoulli Distributed Sequence
BMI – Bilinear Matrix Inequality
CAN – Controller Area Network
CAN-SbW-NEH – CAN-based SbW system with native error handling mechanism
CAN-SbW-PSeC – CAN-based SbW system with per-sample-error-counter mechanism
CRC – Cyclic Redundancy Check
CSMA/CD-AMP – Carrier Sense Multiple Access Protocol with Collision Detection and Arbitration with Message Priority
DbW – Drive-by-Wire
DC – Direct Current
DDP – Data Dropout Probability
DLC – Data Length Code
DM – Deadline Monotonic
ECC – Error Correction Code
ECU – Engine Control Unit
EDF – Earlist Deadline First
EMI – Electromagnetic Interference
FEC – Forward Error Correction
FIFO – First In First Out
GA – Genetic Algorithm
GPP – Generalized Poisson Process
HPP – Homogeneous Poisson Process
IAE – Integral Absolute Error
IEEE – Institute of Electrical and Electronics Engineers
IFS – Interframe Space

ITAE	–	Integral of Time Absolute Error
ILC	–	Iterative Learning Controller
LDP	–	Long Delay Probability
LHP	–	Left Hand Plane
LKF	–	Lyapunov-Krasovskii Function
LMI	–	Linear Matrix Inequality
LQR	–	Linear Quadratic Regulator
LTI	–	Linear Time Invariant
MAC	–	Media Access Control
MADR	–	Maximum Allowable Number of Data Retransmission
MALD	–	Maximum Allowable Loop Delay
MIMO	–	Multi-Input Multi-Output
MTS	–	Mixed Traffic Scheduler
NCS	–	Networked Control System
NEH	–	Native Error Handling
PCB	–	Printer Circuit Board
PSeC	–	Per Sample Error Counter
PSO	–	Particle Swarm Optimization
QoC	–	Quality of Control
QoS	–	Quality of Service
RAM	–	Random Access Memory
REC	–	Receive Error Counter
ROM	–	Read Only Memory
RTA	–	Response Time Analysis
SAE	–	Society of Automotive Engineer
SbW	–	Steer-by-Wire
SISO	–	Single input single output
TbW	–	Throttle-by-Wire
TCP/IP	–	Transmission Control Protocol/Internet Protocol
TDMA	–	Time Division Multiple Access
TEC	–	Transmit Error Counter
TS	–	Takagi-Sugeno
UCP	–	Unit Circle Plane
UPS	–	Uninterruptable Power Supply
ZOH	–	Zero Order Hold

LIST OF SYMBOLS

n_b – Number of data bytes

f_{CAN} – Size of CAN frame

Γ – Message sets

Γ_{sp} – Emergency sporadic data

Γ_c – Control messages

Γ_{nc} – Non-control messages

$\mathbb{T}$ – Messages period sets

T_{sp} – Period or inter-arrival time of emergency sporadic data

T_c – Period of control message

T_{nc} – Period of non-control messages

$\mathbb{L}$ – Transmission time sets of messages

L_{sp} – Transmission time of emergency sporadic data

L_c – Transmission time of control message

L_{nc} – Transmission time of non-control messages

L_{ref} – Transmission time of reference signal data

$\mathbb{D}$ – Deadline sets of messages

D_{sp} – Deadline of emergency sporadic data

D_c – Deadline of control message

D_{nc} – Deadline of non-control messages

$\mathbb{P}$ – Priority sets of messages

P_{sp} – Priorities of emergency sporadic data

P_c – Priorities of control message

P_{nc} – Priorities of non-control messages

τ_{bit} – Bit time

f_{sp} – Frame size of emergency sporadic data

$f_{sc,p}$ – Frame size of p^{th}-sensor data

f_{ca} – Frame size of control signal data

f_{ref} – Frame size of reference signal data

C_e – Control algorithm execution time

B_{max} – Transmission time of the longest possible CAN data (8 bytes), as in $B_{max} = 135\tau_{bit}$

$f_{nc,q}$ – Frame size of q^{th}-non-control data

$L_{c,n}$ – Total transmission time for n^{th}-control message

$L_{nc,s}$ – Total transmission time for s^{th}-non-control messages

l_e – Fault bursts duration

T_e – Fault inter-arrival time within bursts

$\overline{T}_e$ – Mean time between two faults

T_f – Fault inter-arrival time

Q – Random parameter represents number of errors

n_e – The exact value of number of errors

λ_e – Average error arrival rate within bursts

mean(T_e) – Mean of the values in T_e

sum(T_e) – Sum of the values in T_e

R_i – Response time of messages i

J_i – Queuing jitter of messages i

L_i – Transmission time of messages i

W_i – Sum of blocking time during the process of transmitting messages and the interference time due to higher priority message

$hp(i)$ – Messages with priorities higher than messages i

T_j – Period of messages j, where $j \in hp(i)$

L_j – Transmission time of messages j, where $j \in hp(i)$

L_i – Transmission time of messages i

E_i – Overhead frame contributed by error frame and retransmitted frame

f_{max} – Maximum value of frame size, as in $f_{max} = 135$ bits

e_{max} – Maximum value of error frame size, as in $e_{max} = 31$ bits

$T_{e,c}$ – The value of T_e that make control message n become unschedulable

k – Sampling instance

τ_{sc}^{k} – Sensor to controller delay in sampling instance k

τ_{ca}^{k} – Controller to actuator delay in sampling instance k

n_s – Number of sensor node

n^k_{ref} – Number of error occurrences for reference signal data in sampling instance k

$n^k_{sc,p}$ – Number of error occurrences for p^{th}-sensor data in sampling instance k

n^k_{ca} – Number of error occurrences for control signal data in sampling instance k

n^k_{sp} – Number of error occurrences for emergency sporadic data in sampling instance k

L_e – Transmission time of error frame

T_c – Sampling time of control message

n_{nc} – Number of non-control messages

τ_k – Loop delay of sampling instance k

N – Maximum allowable number of error bursts

$\hat{\lambda}_f$ – Error arrival rate for fault model of Theorem 1

$\hat{T}_f$ – Fault inter-arrival time for fault model of Theorem 1

$\hat{L}$ – Evaluation time for fault model of Theorem 1

L – Evaluation time

W_f – Random variable representing value of $\hat{T}_f$

W_e – Random variable representing the value of T_e

$\text{Pr}^{ub}_{L}(W_f < \hat{T}_f)$ – The upper bound for the probability of a message misses its deadline within L

$\text{Pr}^{lb}_{L}(W_f < \hat{T}_f)$ – The lower bound for the probability of a message misses its deadline within L

$\overline{\zeta_c}$ – The upper bound of probability data dropout for control message

$\underline{\zeta_c}$ – The lower bound of probability data dropout for control message

$\text{Pr}(l_e)$ – The probability of fault bursts l_e occurs in interval of L

$\text{Pr}^{ub}_{l_e}(W_e < T_{e,c})$ – The upper bound for the probability of control message misses its deadline within l_e

$\text{Pr}^{lb}_{l_e}(W_e < T_{e,c})$ – The lower bound for the probability of control message misses its deadline within l_e

l_e^{max} – The maximum value of l_e

$E\{\mathcal{X}\}$ – The expectation of the stochastic variables in function $\mathcal{X}$

$\text{Prob}\{\bullet\}$ – The occurrence probability of the event "•"

$\lambda_{max}(\mathcal{A})$ – The largest eigenvalue of $\mathcal{A}$, where $\mathcal{A}$ should be a square matrix

$\lambda_{min}(\mathcal{A})$	–	The smallest eigenvalue of $\mathcal{A}$, where $\mathcal{A}$ should be a square matrix
$\|\mathcal{B}\|$	–	$\sqrt{\mathcal{B}^\top \mathcal{B}}$, where $\mathcal{B}$ should be a square matrix
$\top$	–	Conjugate transpose
$*$	–	An ellipsis for terms induced by symmetry (for symmetric block matrices)
$x(t)$	–	State variables of continuous system
$u(t)$	–	Input of continuous system
A	–	State variables matrices of continuous system
B	–	Input matrices of continuous system
$x(k)$	–	State variables of discrete system
$u(k)$	–	Input of discrete system
$y(k)$	–	Output of discrete system
$r(k)$	–	Reference signal
A_d	–	State variable matrices for discrete system
B_d	–	Input matrices for discrete system
C_d	–	Output matrices for discrete system
$x_s(k)$	–	State feedback to cope data losses
K	–	Gain of state feedback controller
$\overline{K}$	–	Feedforward gain
K_{PSeC}	–	State feedback controller gain for CAN-SbW-PSeC system
K_{NEH}	–	State feedback controller gain for CAN-SbW-NEH system
ρ	–	$\rho = 0$ if data dropout occur, $\rho = 1$ if reference signal data, sensors data and control signal data are successfully transmitted to corresponding nodes
$\overline{\rho}$	–	Data dropout probability
$V(\varepsilon(k))$	–	Lyapunov function of matrix function $\varepsilon(k)$
$\mathcal{D}$	–	Stable region
$f_{\mathcal{D}}$	–	Characteristic function of $\mathcal{D}$ stable region
P_1	–	LMI variable
P_2	–	LMI variable
P_3	–	LMI variable
M	–	LMI variable
$X_{\mathcal{D}}$	–	LMI variable
$\mathcal{S}$	–	Variable in LMI compact form equation

$\mathcal{R}$ – Variable in LMI compact form equation

$\mathcal{S}$ – Variable in LMI compact form equation

$\mathcal{L}$ – Variable in general characteristic function of $\mathcal{D}$ stable LMI region

$\mathcal{M}$ – Variable in general characteristic function of $\mathcal{D}$ stable LMI region

I – Identity matrix

P_1^T – Transpose of matrix P_1

P_2^T – Transpose of matrix P_2

P_3^T – Transpose of matrix P_3

λ – Matrix variable

$\mathcal{U}$ – Matrix variable

$\mathcal{V}$ – Matrix variable

ψ – Matrix variable

R_d – Radius of LMI region disk

q_r – Coordinate of LMI region disk at x-axis

θ_s – Desired value of road wheel angle

θ_r – Road wheel angle

$\dot{\theta}_r$ – Road wheel angular velocity

i_r – Motor current

J_r – Moment of inertia of road wheel

b_r – Viscous damping coefficient

η – Steering ratio

L_r – Motor inductance

V_r – Motor voltage

K_{er} – Electromotive force constant

K_{tr} – Motor torque constant

τ_a – Self aligning torque

τ_f – Friction torque

$C_{\alpha F}$ – Front tire cornering coefficient

g – Gravity acceleration

t_p – Tire pneumatic trail

t_m – Tire mechanical trail

$\mathcal{W}$ – Front tire weight

v – Vehicle velocity

μ – friction coefficient

$\widehat{\mathcal{T}}$ – Average loop delay

$\overline{\mathcal{T}}$ – Maximum loop delay

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CHAPTER 1

INTRODUCTION

1.1 Background of Research

Networked Control System (NCS) is a system where the control loops are closed via network. NCS provides alternative to traditional point-to-point communication by introducing communication line, network nodes and protocols of data handling, which significantly improves the structure of system, thus making the NCS now gaining a popularity in recent years. However, the introduction of a communication network into an NCS can also degrade the overall control system performance due to time delay, data dropout, sampling jitter, data quantization problem, data disorder and messages scheduling problems. Among these problems, time delay and data dropout are more prominent in affecting NCS performance.

Even with many constraints and challenges toward achieving good performance for high end application of NCS, the advantages offered outweigh the difficulties which make the work in this area remains significant. Due to the advantages, such as low cost, simple installation and maintenance, increased system agility and reduced system wiring, NCSs are now applicable to many fields, ranging from DC motors control, advanced aircraft, spacecraft, automotive and manufacturing processes. There are a few excellent literatures that provide more details on NCS. For example, the information in current and future research direction of NCS can be found in [1]. The survey article done in [2] has presented the comprehensive history, classification and research fields that are related to NCS. The results on estimation, analysis and controller synthesis for NCS to handle constraints that exist in NCS are

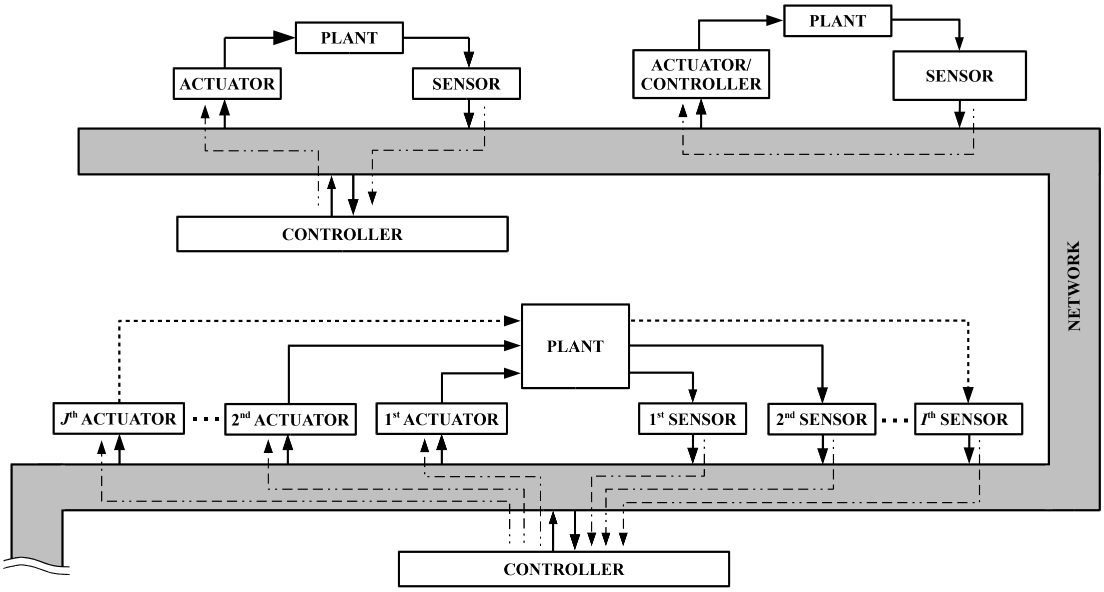

Figure 1.1: Configuration of NCS

presented in [3–5]. The survey of control methodology for NCS to compensate the delay effect can be found in [6,7]. The recent methodologies of event-triggered method for NCS is reported in [8].

Each configuration of NCS consists of sensor, controller and actuator which are interconnected to the same network. It could be constructed by using single sensor and single actuator node, multi-sensors multi-actuators (I sensors and J actuators), or even sensor and actuator-controller combined node, as shown in Figure 1.1. Sensors generate a stream of sensed data and transmit it to controller via network. Controllers process the samples of the sensed data and generate appropriate control signals to be delivered over the network to actuators. Actuators transform control signals into actions that will affect the physical system.

In term of controlling dynamic systems that have strict temporal requirement, high speed serial bus communication has been used as the 'backbone' or the enabler of NCS in the application. Fieldbus technology such as PROFIBUS [9], WorldFIP [10], ControlNet [11], DeviceNet [12], switched Ethernet [13, 14] and controller area network (CAN) are among the most popular fieldbuses that are being adapted in many application especially in automotive and automation equipment.

In brief, PROFIBUS is a master/slave communication system that is developed by Germany researchers in 1980s [9]. WorldFIP also is a master/slave communication system developed by French researchers to compete PROFIBUS technology [15]. ControlNET is developed by Rockwell Automation company in early 2000s and it is a serial communication system that is operated in bus topology network [16]. DeviceNet is also serial communication system but has the ability to support multiple communication hierarchies and it was invented by Allen-Bradlet company in 1990s [17]. Ethernet was initially developed by Xerox company in 1970s and now has become popular and well established local area network (LAN) technology when the internet uses this technology to transmit large number data to remote area at very fast speed and low cost [18].

CAN is an advanced serial bus system designed for short messages transmission and currently it can operate at the speed up to 8 Mbps [19]. It was initially developed for automotive use in late 1980s by Robert Bosch, but now CAN is widely utilized in most real time automation system due to its robustness to electrical interference, predictable behaviour, ability to self diagnose and data error repair, high performances and suitable for harsh environment. Although there are other network types which are faster and able to provide same performance as CAN, but due to low cost and robust protocol, CAN is always the preferred choice for many applications. Furthermore, extensive researches have been carried out in attempt to make the CAN communication link acting as a powerline as well as data transmission medium which promises a greater saving in term of wiring, size and development cost of system in the future [20–27].

In similar line to other types of network, CAN-based system that consists of nodes and bus line are also prone to fault. Fault is known as a threat to dependability of a system which can compromise the ability to deliver service that can justifiably be trusted. Fault is defined as an adjudged cause of an error. An error is known as the part of a system's total state that may lead to a failure. A system is said to have a system failure when the error induced by a fault has cause the delivered service to deviate from the correct state. The framework of this thesis will be focused on fault in network since it is more prominent as compared to fault in network nodes.

The source of these fault could be from environment, human-made or hardware/software problem such as electromagnetic interference (EMI) [28–31], hesienbug [29, 31], intermittent connection [32], unsynchronized clock, malicious activity and intrusion attempt [33]. However, most literatures show that for the system under harsh environment such as in automotive or avionic environment, the source of faults mainly come from EMI [32, 34–36]. For instance, EMI is an unwanted, spurious, conducted, or radiated signal of electrical origin that can cause performance degradation in electronic equipment. Radio equipment, power electronic converter and lightning are a few examples of EMI sources. EMI can potentially affect the correct functioning of network nodes and also causes data transmission error in CAN. EMI problem can be effectively handled at network nodes level, but providing a support to combat EMI at transmission line require expensive facilities especially for long network line [37]. Utilizing fibre optic cable can efficiently eliminate EMI effect, however it is not favoured by the cost-conscious industry due to cost constraints. Shielded cable or filtered connector can be used to reduce the EMI effect to bus line, however, the EMI effect is still exists especially under harsh environment [38, 39].

Fault occurrences in CAN will induce data error which in turn resulting additional transmission delay and/or causing data dropout. Thus it can degrade the performance of NCS. To ensure the stability of NCS, the effect of fault occurrences in CAN should be taken into account when designing NCS. Another concern in an NCS is the error handling feature which is designed to provide error checking mechanism in CAN protocol. The basic idea of error checking is the ability to detect data errors as soon as possible and the system will retransmit the affected messages. In NCS, data retransmission feature is favourable since it helps to recover data losses and maximizing network bandwidth. However, this feature could lead to uncontrolled number of retransmitted data and consequently causing bandwidth overload and thus leading to performance deterioration and system instability. Hence, this mechanism need to be replaced with other more effective error handling protocol which is capable to optimize the number of retransmitted data.

1.2 Problem Statements

There are a few problems arise in designing a CAN-based NCS under network fault conditions:

I. The native error handling of data handling protocol in CAN performs the data retransmission of erroneous data until it is successfully transmitted. This process will introduce additional delay and may lead to network congestion and thus it is not suitable for real time requirement.

II. Fault in CAN will induce additional delay and/or data dropout which can degrade the performance of NCS. However, there is no relationship that can be associated between fault parameters and NCS parameters that can influence the NCS performance. This problem has obscured the development of NCS model under fault conditions and thus lead to difficult controller design and analysis.

III. The transmission delay and data dropout that occur for sensor data and control signal data can degrade or destabilized the performance of NCS. The controller that are designed without consideration of delay and data dropout cannot guarantee the stability of NCS when the system experience delay and data dropout.

1.3 Objectives

The aims for this research are as the followings:

I. To develop the strategies to handle the fault occurrences in CAN in order to properly analyse the effect of the fault to CAN-based NCS performance.

II. To build a control algorithm for NCS which can compensate the delay and data dropout effects that are introduced by fault occurrences in CAN.

III. To verify the efficacy of developed fault handling strategies and designed control algorithm through extensive simulation.

The main contributions of this work are achieved by completing these three objectives.

1.4 Scopes of Work

Scopes of this project are:

I. **Fault in CAN of single loop NCS**

Fault may occur in network nodes and transmission line. Also the NCS may consist of several loops on the same network. In this work, only fault in transmission line on single loop NCS will be covered.

II. **Strategies to handle fault occurrences in CAN**

The strategies that are proposed to handle erroneous data due to fault occurrences in CAN will cover the development of fault and messages model, messages scheduling theory and probability theory. These strategies are purposely to bound transmission delay and also to give an information on data dropout probability.

III. **Modelling of NCS and control algorithm design**

The modelling of NCS in CAN will be performed by considering the transmission delay and data dropout probability into the system. Then the control algorithm of NCS will be designed subjected to Lyapunov-based stability conditions. The synthesis of controller gain will be determined by using linear matrix inequality (LMI).

IV. **Simulation**

The simulation of designed control algorithm will be applied to steer-by-wire (SbW) system. The system is arranged into third order linear time invariant (LTI) system with disturbances. To find the solution of developed LMI sets, Yalmip/Sedumi solver will be used since it produce less conservative result as compared to LMI Control Toolbox that provide in MATLAB®/Simulink. Also to verify the efficacy of the proposed strategies, MATLAB®/Simulink-based TrueTime simulator will be extensively utilized.

1.5 Contributions of the Research Works

The following are the main contributions of the study:

I. A new equation of response time analysis (RTA) under error busts which is presented in Section 3.2.2. If the value fault bursts duration and fault inter-arrival time within fault bursts are known, the equation can provide a schedulability analysis under fault bursts.

II. A new error handling algorithm has been introduced in Section 3.3.1 to replace the native error handling in CAN. This mechanism has been designed to be applied in single loop CAN and can prevent network congestion, thus providing suitable environment for CAN-based NCS under network fault conditions.

III. A new proposition statement has been developed in Secion 3.3.2 which enable the fault parameters to be associated to the parameters that are influencing NCS performance, namely loop delay and data dropout probability.

IV. A new theorem has been derived in Section 3.4.2 to provide the synthesis of state feedback controller for NCS with bounded delay and data dropout. This theorem has been developed based on Lyapunov stability approach formulated based on LMI.

1.6 Thesis Outline

This thesis consists of five chapters and are organized as the followings: Chapter 2 provides a literature review on the CAN, fault occurrences and NCS. First, the background of CAN-based NCS and fault occurrences is discussed in term of NCS history, justification of choosing CAN and fault occurrences in networked system. Afterwards, a research trend in CAN is presented to discover the research opportunity or issues that arise in CAN applications. The research of NCS design under delay and data dropout in recent years are also presented.

Chapter 3 consists of three sections presenting the methodology for error handling and controller design for CAN-based NCS. Section 3.2 discusses the framework of CAN messages and fault occurrences in CAN-based NCS which serve as the basis of this work. The explanation on CAN regarding frame format, data transmission protocol and data error handling are done at prior before establishing the messages and fault model. The RTA under network fault conditions is also developed to provide pessimistic schedulability test for control message. A probability theory and message scheduling theory are utilized in the development process. Then, Section 3.3 covers the development of a new error handling algorithm which is designed to provide more suitable data error management in NCS environment. The calculation to determine the data dropout probability for control message is also incorporated in this section. Then, in Section 3.4, the NCS model with delay and data dropout is developed, subsequently the stability and stabilization condition derivation is performed based on Lyapunov stability theory to design a controller that can compensate the effect of delay and data dropout. The pole clustering technique of LMI region is also introduced as a supplementary to controller design to obtain the desired transient response.

Chapter 4 provides an extensive analysis of simulation work to investigate the effectiveness of the proposed strategies to handle fault in CAN-based NCS. SbW system is chosen as a testbed since it is the most critical automotive system in drive-by-wire (DbW) technology. A brief explanation on this system is also included in the chapter.

Finally in Chapter 5, the summary of the results of this research is presented. The suggestions of future works for improvement, extension and continuity of this research are also covered.

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