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

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

MOHD BADRIL BIN NOR SHAH

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
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JULY 2015

I declare that this thesis entitled *"Error Handling and Controller Design for Controller Area Network-based Networked Control System"* is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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

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Badril Nor Shah, Kangkar Pulai, Johor, February 2015

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.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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 "$\bullet$"
$\lambda_{max}(\mathcal{A})$	–	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

LIST OF APPENDICES