DATA SAMPLING TIME SCHEDULING BASED ON MAXIMUM ALLOWABLE LOOP DELAY FOR NETWORKED CONTROL SYSTEM

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To my dearly beloved husband, Radin Luqman bin Salihuddin for his support,encouragement and blessing
To my dearest parents and parents in law for their love and understanding
To my little Caliphs, Radin Akif and Radin Anas for making my life beautiful and cherish

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ABSTRACT

Networked Control System (NCS) has gained the popularity recently due to low installation and maintenance cost, high reliability, and less wiring. This control approach of NCS differs from traditional control system since controller and plant are physically separated and connected through a communication network. Despite these advantages that the system offers, the main challenge of NCS is networked-induced delay that occurs while data is exchanged between components. Data Sampling Time scheduling with Offset (DSTOS) algorithm is an existing method and one of the effective approaches developed to handle time delays τ by allocating data according to priority for linear order system. In this work, the NCS of non-linear 2-link planar robot is developed based on Controller Area Network (CAN) where Proportional and Derivative (PD) controller is adapted to form a closed loop system. Based on this configuration, DSTOS algorithm is reconfigured for non-linear system and implemented such that the assignment of message priority is assigned according to the calculated Maximum Allowable Loop Delay (MALD) in every loop to reduce network delay. The NCS of 2-Link planar robot is formed based on two loops which consist of two sensor nodes, two actuator nodes and two controller nodes that perform data exchange in CAN 2.0A data frames under various CAN speeds. Simulations are performed by using MATLAB/SIMULINK with TrueTime Toolbox. Analysis of simulation results shows that the CAN-based non-linear system is able to accommodate this method and meets the real time and control requirements. By using DSTOS algorithm, the maximum data latency of control loops is reduced by almost 15% as compared to system without DSTOS. The reduction in link angle error is evident based on low value of IAE index. DSTOS also promotes lower energy consumption of DC servomotor which is important especially for industry.

ABSTRAK

Sistem Kawalan Rangkaian (NCS) semakin popular di akhir ini disebabkan kos pemasangan dan penyelenggaraan rendah, kebolehpercayaan tinggi dan kurang pendawaian. NCS berbeza daripada sistem kawalan tradisional kerana pengawal dan loji secara fizikalnya berasingan dan bersambung melalui satu rangkaian komunikasi. Walaupun menawarkan banyak kelebihan, cabaran utama NCS adalah lengah masa oleh rangkaian teraruh semasa data ditukar antara komponen. Algoritma penjadualan masa dan Persampelan Data Berserta Ofset (DSTOS) adalah salah satu kaedah sedia ada dan efektif dibangunkan untuk mengawal lengah masa τ dengan memperuntukkan data mengikut keutamaan bagi sistem lelurus. Dalam penyelidikan ini, NCS robot 2-lengan satah bukan-lelurus dibangunkan menggunakan Pengawal Rangkaian Kawasan (CAN) di mana pengawal Perkadaran dan Pembezaan (PD) telah disesuaikan untuk membentuk satu sistem gelung tertutup. Berdasarkan konfigurasi ini, algoritma DSTOS diadaptasi untuk sistem bukan-lelurus dan dilaksanakan supaya keutamaan data ditentukan mengikut kiraan Kelewatan Masa Maksimum Dibenarkan (MALD) dalam setiap gelung bagi mengurangkan lengahan masa. NCS 2-lengan satah robot dibentuk berdasarkan dua gelung, terdiri dari dua nod pengesan, dua nod pemacu dan dua nod pengawal melakukan pertukaran data dalam bingkai data CAN 2.0A mengikut kelajuan CAN yang berbeza. Penyelakuan ini menggunakan MATLAB/SIMULINK dengan Penyelaku *TrueTime*. Analisa keputusan penyelakuan menunjukkan sistem bukan-lelurus berdasarkan CAN mampu menampung kaedah ini dan memenuhi masa sebenar dan keperluan kawalan. Dengan menggunakan algoritma DSTOS, peratusan bagi maksimum lengah masa data bagi gelung kawalan menurun hampir kepada 15% berbanding tanpa DSTOS. Pengurangan pada ralat sudut lengan terbukti berdasarkan nilai rendah indeks IAE. DSTOS juga menggalakkan penggunaan tenaga lebih rendah oleh DC motor servo yang sangat penting terutama di dalam industri.

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LIST OF ABBREVIATIONS

NCS	-	Networked Control System
CAN	-	Controller Area Network
DC	-	Direct Current
MALD	-	Maximum Allowable Loop Delay
DbW	-	Drive-by-Wire
Profibus	-	Process Field Bus
FMS	-	Field bus Message Specification
DP	-	Decentralized Peripherals
FP	-	Fixed Priority
DMS	-	Deadline Monotonic scheduling
EDF	-	Earliest Deadline First
CSMA	-	Carrier Sense Multiple Access
BA	-	Bitwise Arbitration
CD	-	Collisions Detection
MTS	-	Mixed Traffic Scheduling
RM	-	Rate Monotonic
LMI	-	Linear Matrix Inequality
DOF	-	Degree-of-Freedom
PD	-	Proportional Derivative
DSTOS	-	Data Sampling Time Scheduling with Offset
DSTS	-	Data Sampling Time Scheduling
PID	-	Proportional Integral Derivative
PI	-	Proportional Integral
I/O	-	Input Output

bps - bite per second

LIST OF SYMBOLS

Φ – maximum allowable delay bound

L_e – Transmission time of event data packet

L_c – Transmission time of control data packet

M – Number of Loop

T_i – Sampling Time

K_p – Proportional Gain

T_i – Integral Gain

T_d – Derivative Gain

J_1, J_2 – Moment of inertias of arm 1 and 2

J_{m1}, J_{m2} – Inertias of motors 1 and 2

m_1, m_2 – Masses of arm 1 and 2

L_{a1}, L_{a2} – Armature Inductances of motors 1 and 2

R_{a1}, R_{a2} – Armature Resistances of motors 1 and 2

K_{e1}, K_{e2} – Inverse emf coefficients of motors 1 and 2

K_{T1}, K_{T2} – Torque coefficients of motors 1 and 2

r_1, r_2 – Lengths of arms 1 and 2

N_1, N_2 – Gearbox ratios of motors 1 and 2

$\theta_1, \dot{\theta}_1, \ddot{\theta}_1$ – angular displacement(link angle), velocity and acceleration of link 1 arm $rad, rad/s, rad/s^2$

$\theta_2, \dot{\theta}_2, \ddot{\theta}_2$ – angular displacement(link angle), velocity and acceleration of link 2 arm $rad, rad/s, rad/s^2$

θ_{m1}, θ_{m2} – motor angles of link 1 and link 2

P_x, P_y – horizontal robot coordinates

M – Number of control loops interconnected into CAN bus

N_c – Number of nodes that generate control data

N_e – Number of nodes that generate event data

N_n – Number of nodes that generate non-real-time data

L_c – Transmission time of control data packet

L_e – Transmission time of event data packet

L_n – Transmission time of non-real-time data packet

$\Phi_i, i = 1 - M$ – Maximum allowable loop delay of control loop i

γ – interval,windows

α_k – maximum number of data generated during interval γ

T_i, i=1 $- M$ – Sampling interval of control loop i

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Research

A control system is mainly composed of interconnected components which include sensor, controller, actuator and the physical system or plant. The traditional point-to-point architecture has been successfully implemented in many control systems where sensors and actuators are directly wired to the controller and the controller usually serves as the main ”brain” of the system. However, with the advancement of technologies and the increase complexities in many system design, this conventional architecture seems inadequate to accommodate the design requirement and may be lacking to address the issue of reliability and compatibility required by industrial need for distributed control. Thus, the traditional point-to-point architecture system in industries is getting less favourable in many systems and being replaced by distributed control system connected via communication network. This new alternative, or formally named Networked Control System (NCS), is a feedback control system wherein control loops are closed by means of real time control network and components are physically separated and connected through the network as shown in Figure 1.1.

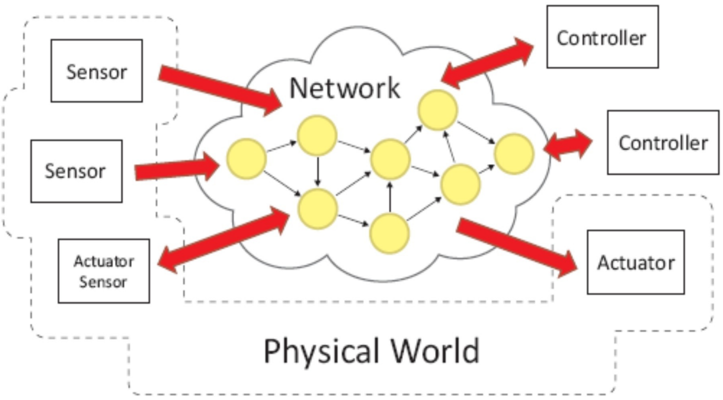
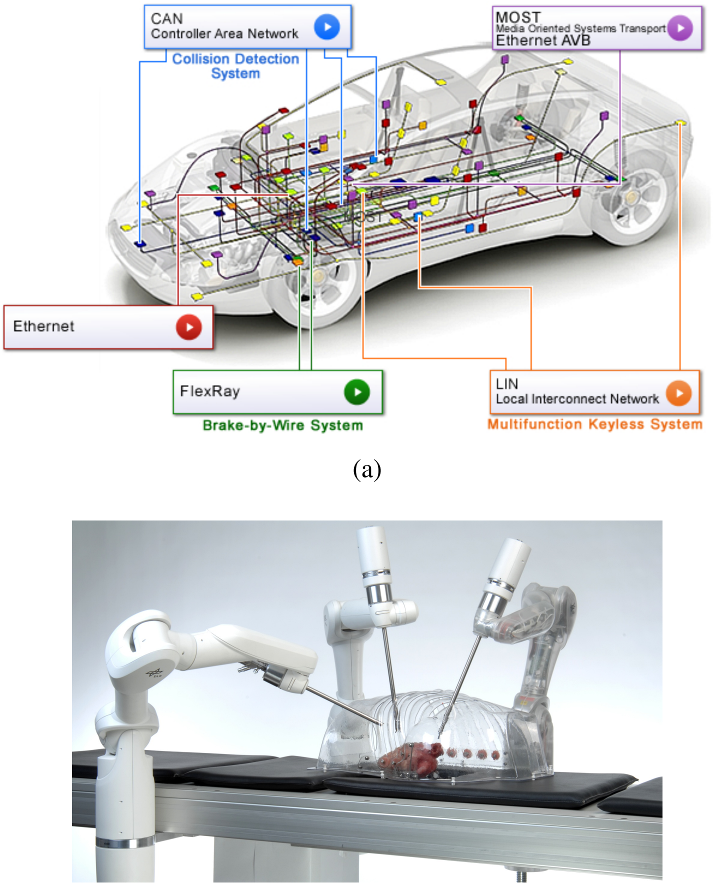


Figure 1.1: A typical networked control [3]

The demand of networks as a media to interconnect components in industrial control system is gaining attention due to development in the area of communication and computer network technologies. The technologies have made it possible to include communication on feedback control loop yet achieving real-time requirements. The trend in modern industrial and commercial system is to integrate control system, communication network and computing into higher levels of industrial operation and information processes. This technology provides various communication line, network nodes and protocols of data handling to be integrated which improved structure of the system. This structure consequently eliminates the unnecessary wiring thus increasing system agility and reducing the overall cost in designing and implementing the control system. Obviously the vast development of communication network technologies has contributed significantly and become more common in many fields ranging from DC motors, auto-mobiles, aircraft, manufacturing and robotics. Figure 1.2 (a) shows an NCS of drive-by-wire (DbW) system in automotive where the connection of various components forming the real-time network system are achieved by adapting Controller Area Network (CAN), Local Interconnect Network (LIN), Ethernet, FlexRay and

Media Oriented System Transport (MOST). Each of this network type has its own communication structure and protocol which leads the network in the automotive to be very heterogeneous in data type and exchange mechanism yet able to achieve the overall system requirement [6]. Figure 1.2 (b) illustrates another example of NCS which is the cooperation of a few robots to perform surgery locally or remotely (tele-operation). The sensors, actuators and the control system are arranged in network based architecture to perform real-time task with each of the data inherit time criticality in term of timeliness of the data exchange [7].



(a)

(b)

Figure 1.2: Example of NCS based control system (a) CAN based Drive-by-Wire and (b) Surgery robot [4, 5]

Despite the importance of the NCS-based control systems, there are issues arise in NCS development mainly the time delay experienced by the transmitted data which occurs due to the protocol of the network system. The time delay has variable length and predefined limit which mostly dependant on the configuration of the control system. Typically, there are three type of data generated from sensor and controller and these data share the bandwidth of the common network medium. It is crucial to control efficiently the traffic of data generated through network medium such that the time delay does not exceed its maximum bound, or named as maximum allowable loop delay (MALD). The consideration of the MALD in the NCS design is vital as some control systems are prone to have low performance in real time and control aspects [8] and even, in the worst case, destabilize the system [4].

This time delay of data inherited in NCS is rather different from typical direct control system because the delay in NCS is dynamic and non-linear in nature and this makes the task of measuring and developing the relation between the delay and the system specification remain a challenging issue. Among the many methods to reduce the delay, the goal is to propose an appropriate traffic scheduling of the data such that maximum delay requirement is met and furthermore will not influence the performance of application system. Data sampling time scheduling is one of effective approaches developed to handle the time delays, τ, by allocating the data according to priority and the network will be fully utilized in term of its bandwidth as well as the delay or data latency of the control data is less than the MALD [9]. The method is performed by assigning different data sampling time, T_i for different control loops and the sampling time of individual control loop is determined by finding the MALD and the availability of the network bandwidth. The methodology is originally used for multiple control loop of NCS on a periodic delay network, however, in many existing control system, the delay is very random and in many cases are un-deterministic. In very specific type of real-time network such as CAN, the approach has to accommodate the transmission protocol of the network. In addition, a few researchers have been evaluated the algorithm in linear system, such as DC motor [10] and other system [11, 12] however, in non-linear system where the delay is more dynamic there, however, has not been any report on the application of the scheduling method in the non-linear system. Due to the promising performance of the method in reducing the delay in control system, this serves as an excellent research opportunity to be able to accommodate the method in non-linear system and further to assess the performance, both in term of real time and control.

1.2 Statement of the problems

The existence of the communication network in control system introduces time delay due to the exchange of data between the NCS components. The delay leads to the instability of the system performance which from congested network traffic or data loss during the transmission. The time delays can vary widely according to the transmission time of data, the overhead time and the number of transmitting nodes in the system. From the control point of view, the stability of the control system can be guaranteed by transmitting the sample data within or less than a sampling period while most control systems prefer shorter sampling period so that the system can accommodate other necessary non-real time tasks and also to guarantee favourable performance is to be achieved.

Since the system performance is dependant to the loop delay, it is required to choose the period to length up to a certain MALD such that the stability of the control loop is guaranteed. Loop delay is measured from the instant when sensor node samples sensor data to the instant when data receive at actuator node. Sampled data at the sensor and controller nodes have to wait at the transmitter queue and this arbitration mechanism introduces the main delay component in the network. When the delay happens to be greater than the data sampling time interval, more than one sensor data will arrive in the next same period of controller sampling intervals and, thus, only the current sensor data is used to generate controller signal. This situation will cause the occurrence of data rejection. On the other hand, when no sensor data arrives in the controller sampling interval, this will result in the vacant sampling. Both the phenomena of data rejection and vacant sampling are illustrated in Figure 1.3.

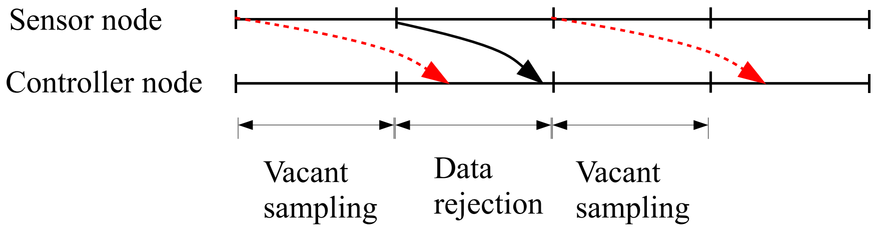


Figure 1.3: Data rejection and vacant sampling

Data rejection and vacant sampling not only degrades control performance but also introduces distortion of the controller signal. The distortion of control input causes high frequency noise in the actuator leading to excessive wear of the mechanical parts [13]. Thus, in NCS, it is high fidelity that every sensor data should arrive at the controller node before the next sensor data is sampled, as to ensure the desired system performance can be achieved. In order to achieve this objective, the transmission of these data has to be assigned in some coordinated order to avoid traffic congested so that the delay does not exceed the pre-defined limit for each control loop.

The existing algorithm of calculating the sampling time based on MALD and assigning the offset for control data has been formulated in [14] and improved in [9]. However, both of the algorithms have been implemented in linear system which does not portray the actual complexity of NCS in non-linear dynamic system. The reformulation and adaptation of the algorithm such that it is implementable in non-linear systems that inherit to some degree of complex dynamic can be considered as good research opportunity. This is to illustrate that the delay in NCS for non-linear of dynamic system can be minimized by formulating effective scheduling algorithm.

1.3 Research Objectives

The objectives of the research can be established as follows:

1. To reconfigure the model of network based industrial robot based on CAN to be the platform of NCS for dynamic system.
2. To reformulate the off-line sampling times scheduling algorithm which is calculated based on MALD of individual loop of control system connected over CAN.
3. To verify the efficacy of the algorithm in CAN-based network control system by means simulation.

1.4 Scope of Study

The scopes of the work can be limited to the followings:

1. 2-Link Planar robots are to be used as the dynamic system.
2. CAN network is used as the field-bus to connect the sensors, actuators and controller of the robot.
3. Verification is performed in simulation environment by using TRUETIME, a MATLAB/Simulink based simulator for real-time control systems.

1.5 Thesis overview

Throughout the thesis, the reason of study are carefully narrated in first chapter. The background and some literatures on the field-bus technologies, the scheduling on NCS and the specific CAN based networked control system is described in Chapter 2. The scheduling algorithm of data sampling time is discussed and implemented to the established dynamic system as well as the preparations for simulation model is presented in the Chapter 3. Simulations result and analysis of the developed simulation model are discussed for various cases as presented in Chapter 4. Finally, conclusion and recommendations are made in Chapter 5.

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