CO-DESIGN-BASED EVENT-TRIGGERED PROPORTIONAL INTEGRAL CONTROLLER UTILIZING FIXED PERIOD AND COMBINED TRIGGERING MECHANISM ALGORITHMS FOR CYBER-PHYSICAL SYSTEM

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

MARCH 2023

DEDICATION

To my dearest late parents, Md Yusop Salleh and Sariah Rasan for their love, blessing and prayers.

To my beloved wife, Rohaida Mat Akir for her understanding, love encouragement and continuous support over the years.

To my family for their extensively love and their endless support.

ACKNOWLEDGEMENT

In the Name of Allah, the Most Gracious and the Most Merciful, Who always keep me under His guidance and grant me strength throughout this journey.

I wish to particularly express my deepest appreciation to my main supervisor, Professor Dr. Zaharuddin Mohamed and previous supervisor Associate Professor Dr. Rosbi bin Mamat, for their encouragement, guidance, and constructive criticism to unleash my potential and improve my research skills. Without their continued patience, support, critical comments, and guidance, this research would not be the same as what is presented here. They also provided a limitless inspiration in my research and for my future career.

I would also like to show my warmest gratitude to my research colleagues, Dr. Haziq, Dr. Saiful, Dr. Hazriq, Dr. Izzuddin, Dr. Waqas, Dr. Asraf, Mr. Hassan, Mr. Faseh and Mr. Firdaus for being my research partners. Their views and support are really helpful throughout this research

I would also like to thank the Head and assistant engineer of P08 Robotic Lab, Associate Professor Dr. Hafiz and Mr. Rukaini for their support and services during my work in their lab. Thank also for always cheering me up during the tea time.

I am also thankful to Universiti Teknologi Malaysia (UTM) for the facilities and services provided throughout my study. Also, I would like to express my deepest gratitude to my employee and my sponsor, Jabatan Tenaga Manusia (JTM), Ministry of Human Resources (MOHE), and Jabatan Perkhidmatan Awam (JPA) for their support in term of the scholarship.

My family members deserve the utmost credit in this achievement. In particular, I would like to express my gratitude to my late parents, Hj. Md Yusop and Hjh Sariah, who always encourage me to do my best, and always remember me in their prayers. Same goes to my siblings, Norizan and Saiful, who offered invaluable support and humour over the years.

Last but certainly never least, I want to thank my beloved wife who is also my study partner since bachelor’s degree, Rohaida Mat Akir for her love, understanding, patience, and support.

ABSTRACT

Cyber-physical systems (CPSs) are integrated systems where the physical process incorporates cyber components which include computation and communication/networking. The integration is usually in the form of a feedback loop, in which the cyber component constantly monitors and controls the physical process. Conventionally, a controller is designed only to achieve a physical goal, bringing the physical output to the desired setpoint with specific performance criteria. On the contrary, CPS needs to take into account both cyber and physical performances by enhancing the integration between both elements. As a result, a co-design approach is required to support the CPS feedback controller design that has the capability to reduce the cyber energy while maintaining the physical performance as the integration enhancement criteria. Due to this benefit, the CPS has started to be implemented for control of process plants. This thesis presents two improved event-based Proportional-Integral (PI) controllers, namely Fixed Period Algorithm (FPA) and Combined Triggering Mechanism Algorithm (CTMA), as CPS feedback controllers for industrial process control. The FPA and CTMA are procedurally designed according to the new co-design framework, where the FPA is designed to reduce the control computation algorithm while the CTMA mitigates the sticking and limit cycles issues. The framework consists of controller design, trade-off design, and design's evaluation processes. A conventional PI is initially designed, then the integration's enhancement is introduced by using the event-based strategy in trade-off design, hence producing the FPA and CTMA. The development of FPA and CTMA are based on previous event-based PI controllers, namely Durand and Marchand Saturation Algorithm (DMSA) and Durand and Marchand Hybrid Algorithm (DMHA). The CTMA is an extension of FPA that combines absolute and relative errors as a triggering mechanism. By using an improved algorithm, FPA and CTMA reduce the control computation algorithm by 25% (2.4 pJ) and more than 64% (12.8 pJ) as compared to DMSA and DMHA, respectively. The performances of FPA and CTMA in reducing control updates are also compared to DMSA and DMHA for the case with and without network delays on the lag-dominant, balance, and delay-dominant processes. Network delays are represented by constant and time-varying delays, where the maximum delay values are determined using a simple stability criteria and Monte Carlo simulation in the design's evaluation process. It is found that CTMA reduces control updates by 50% for the lag-dominant process and 10% for the balanced process based on simulation results without the presence of delay. With the presence of delays, the superiority of the CTMA is confirmed especially for the lag-dominant process, where CTMA improves approximately 50% of the computational load reductions and 70% of the physical performance compared to DMHA. Another intriguing discovery is that the FPA can achieve comparable performance to the DMHA despite using a simpler computation algorithm. Taken together, the clear benefits of FPA and CTMA are the trade-off designs that reduce the computational energy by reducing the control updates while maintaining the physical performance. It is envisaged that FPA and CTMA can be utilised for efficient CPS feedback control in industrial process control.

ABSTRAK

Sistem siber-fizikal (CPS) ialah sistem bersepadu di mana proses fizikal menggabungkan komponen siber yang merangkumi pengiraan dan komunikasi/rangkaian. Penyepaduan biasanya dalam bentuk gelung suap balik, di mana komponen siber sentiasa memantau dan mengawal proses fizikal. Secara konvensional, pengawal direka bentuk hanya untuk mencapai matlamat fizikal, membawa proses fizikal ke tetapan yang dikehendaki dengan kriteria prestasi tertentu. Sebaliknya, CPS perlu mengambil kira prestasi siber dan fizikal dengan mempertingkatkan integrasi antara kedua-dua elemen. Akibatnya, pendekatan reka bentuk bersama diperlukan untuk menyokong reka bentuk pengawal suap balik CPS yang mempunyai keupayaan untuk mengurangkan tenaga siber disamping mengekalkan prestasi fizikal sebagai kriteria peningkatan integrasi. Disebabkan oleh faedah ini, CPS telah mula dilaksanakan untuk kawalan loji proses. Tesis ini membentangkan dua Pengawal Kamiran-Perkadaran (PI) berasaskan-peristiwa, iaitu Algoritma Tempoh Tetap (FPA) dan Algoritma Gabungan Mekanisme Pencetusan (CTMA), sebagai pengawal suap balik CPS untuk kawalan proses industri. FPA dan CTMA direka bentuk mengikut aturan rangka kerja reka bentuk bersama yang baharu, di mana FPA direka untuk mengurangkan algoritma pengiraan kawalan manakala CTMA mengurangkan isu keluaran melekat dan kitaran had. Kerangka ini terdiri daripada reka bentuk pengawal, reka bentuk tukar-ganti, dan proses penilaian reka bentuk. PI konvensional direka bentuk sebelum peningkatan integrasi diperkenalkan dengan menggunakan strategi berasaskan-peristiwa dalam reka bentuk tukar-ganti, justeru menghasilkan FPA dan CTMA. Pembangunan FPA dan CTMA adalah berdasarkan pengawal PI berasaskan-peristiwa sedia ada, iaitu Algoritma Tepu Durand dan Marchand (DMSA) dan Algoritma Hibrid Durand dan Marchand (DMHA). CTMA ialah pelanjutan FPA yang menggabungkan ralat mutlak dan relatif sebagai mekanisme pencetus. Dengan menggunakan algoritma yang ditambah baik, FPA dan CTMA mengurangkan algoritma pengiraan kawalan sebanyak 25% (2.4 pJ) dan lebih daripada 64% (12.8 pJ) berbanding dengan DMSA dan DMHA. Prestasi FPA dan CTMA dalam mengurangkan kemas kini kawalan juga dibandingkan dengan DMSA dan DMHA untuk kes dengan dan tanpa kelewatan rangkaian pada proses loji dominan susulan, dominan seimbang dan dominan lewat. Kelewatan rangkaian diwakili oleh kelewatan malar dan kelewatan masa yang berubah-ubah, di mana nilai kelewatan maksimum ditentukan dalam proses penilaian reka bentuk menggunakan kriteria kestabilan mudah dan simulasi Monte Carlo. Adalah didapati bahawa CTMA mengurangkan kemas kini kawalan sebanyak 50% untuk proses dominan susulan dan 10% untuk proses seimbang berdasarkan hasil simulasi tanpa kehadiran kelewatan. Dengan adanya kelewatan, keunggulan CTMA disahkan terutamanya untuk proses yang dominan susulan, di mana CTMA menambah baik kira-kira 50% daripada pengurangan beban komputasional dan 70% daripada prestasi fizikal berbanding DMHA. Satu lagi penemuan yang menarik ialah FPA boleh mencapai prestasi yang setanding dengan DMHA walaupun menggunakan algoritma pengiraan yang lebih mudah. Secara keseluruhan, faedah jelas FPA dan CTMA ialah reka bentuk tukar-ganti yang mengurangkan tenaga komputasional dengan mengurangkan kemas kini kawalan sambil mengekalkan prestasi fizikal. Adalah dijangkakan bahawa FPA dan CTMA boleh digunakan untuk kawalan suap balik CPS yang cekap dalam kawalan proses industri.

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LIST OF ABBREVIATIONS

ADC	-	Analog Digital Converter
AMIGO	-	Approximate M-constrained Integral Gain Optimization
CPS	-	Cyber-Physical System
CTMA	-	Combined Triggering Mechanism Algorithm
CTMEA	-	Combined Triggering Mechanism Extra Algorithm
DAC	-	Digital to Analog Converter
DMHA	-	Durand And Marchand Hybrid Algorithm
DMSA	-	Durand And Marchand Saturation Algorithm
ETC	-	Event Triggered Control
FPA	-	Fixed Period Algorithm
FPEA	-	Fixed Period Extra Algorithm
FOPDT	-	First Order Plus Deadtime
IAE		Integral Absolute Error
IAU		Integral Absolute Control Effort
LQR	-	Linear Quadratic Regulator
LQG	-	Linear Quadratic Gaussian
MPC	-	Model Predictive Control
MCS	-	Monte Carlo Simulation
NCS		Networked Control Systems
NIST		National Institute of Standards and Technology
ODE	-	Ordinary Differential Equation
PI	-	Proportional Integral
PID	-	Proportional Integral Derivative
RTS	-	Real Time System
SIMC	-	Simple Internal Model Control
SOD	-	Send on Delta
SSOD	-	Symmetry Send on Delta
ZOH	-	Zero order Hold

LIST OF SYMBOLS

$e(t_k)$	-	Current error
$e(t_j)$	-	Previous error used by controller
$e^*(t)$.	-	Generalize error
$u(t)$	-	Control signal
elim	-	Triggering limit
K_p	-	Static gain
τ	-	normalized dead-time
L	-	Delay
T	-	Time constant
K_c	-	proportional gain
T_i	-	integral time constant
H	-	Step size
$u(t_k)$	-	Control signal
$u_p(t_k)$	-	Proportional control
$u_i(t_k)$	-	Integral control
M_s	-	Nominal sensitivity peak
h_{nom}	-	Sampling time
h_{act}	-	Interval time without event.
h_{max}	-	Maximum interval time without event
δlim	-	Triggering limit for CTMA
L_m		Maximum allowable delay for stability from MCS
L_{mc}	-	Maximum allowable delay for stability from stability analysis
L_{mp}	-	Maximum allowable delay for performance

CHAPTER 1

INTRODUCTION

1.1 Research Background

In the first two decades of the 21st century, the technologies of computer, communication, and control systems have grown rapidly. This technological development creates sophisticated systems that involves the integration of these fields. These integration systems are called as cyber-physical systems (CPSs). CPS was coined in 2006 by Helen Gill, the director of computer information and science engineering (CISE) at National Science Foundation (NSF) USA (Lee and Seisha, 2017). The NSF (NSF, 2021) defines CPSs as “engineered systems that are built from, and depend upon, the seamless integration of computation and physical components to enable the capability, adaptability, scalability, resiliency, safety, security, and usability that will expand the horizons of the system”. Lee (2015) states “CPS is an orchestration of computers and physical systems. Embedded computers monitor and control physical processes usually with feedback loops, where physical processes affect computations and vice versa”. While, the National Institute of Standards and Technology (NIST) defines CPS as “a system that integrate the cyber world with the physical world, where computational and physical components of such systems are tightly interconnected and coordinated to work effectively together, sometimes with humans in the loop” (NIST, 2013). Other researchers have come to an agreement that CPS is the next generation of engineered systems that require tight integration of computing, communication, and control techniques (Raj *et al*., 2010; Kim and Kumar, 2012; Sztipanovits *et al*., 2012).

From all the definitions, there are some common characteristics that can be extracted. In inference, CPS has the following characteristics (Guan, *et al.*, 2016):

a. Integration of cyber elements (computation, software, and networking) and physical elements (engineered systems and human factor).

b. A feedback loops system which involves the physical processes, computations (simulation and decision making), sensing and actuation elements, and monitoring and control elements.

c. Networked, tightly coupled, interconnected processes and mediating between computing and physical entities.

Figure 1.1 shows the relationship between cyber and physical spaces for CPS which makes CPS a heterogeneous system that combines hardware, software, sensors, actuators, and other components (Parnianifard *et al.*, 2020). Basically, CPS is a system that integrate several systems, such as embedded systems, networked control systems (NCS) and Internet of Things (IoT). Therefore, the analysis and design of the CPS are based on unified dynamics, which emerge from interactions between physical, computer, software, and networks (Seshia *et al.*, 2017) and the main difference between CPS from embedded system and NCS is the requirement for integration's enhancement of the cyber and physical elements. Table 1.1 summarises the differences between CPS and NCS in a control system perspective.

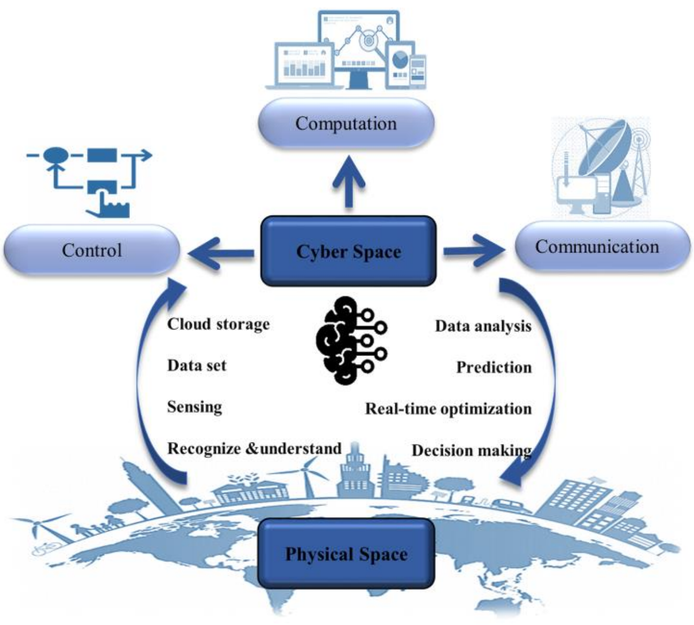

Figure 1.1 CPS relationships (Parnianifard *et al.*, 2020)

Table 1.1 Differences between CPS and NCS

CPS	NCS
System of system – consist of several subsystems (Seshia *et al*., 2017).	Subsystem of CPS.
Focus on the integration between cyber and physical worlds, with more considerations given to the cyber part of control design (Lee, 2017).	Focus on the stability of the designed controller to mitigate the network issues.
Autonomous control operation where the cyber part is able to react accordingly to physical state and vice versa (Kopetz, 2019).	The cyber part only for computing control signal, and transferring data between sensor, controller and actuator.

CPS is frequently referred to a large-scale system, which complicates its integration. As suggested in Kopetz (2019), the complexity of the integration can be reduced using a partition technique, where the integration's enhancement can be applied within every CPS sub-domain. As an example, the integration can be implemented in the embedded system or in NCS itself. As illustrated in Figure 1.1, the control system is one of the CPS sub-domains, in which the cyber part plays a role in computing a control signal for the actuator using an information from the sensor in feedback closed-loop control. The feedback loops that constantly transfer and compute the control signal every predefine sampling time will keep utilizing the cyber energy. So as to enhance the integration of cyber and physical parts, this computation cost can be included as an objective in controller design by allowing the trade-off between cyber and physical performances (Bradley and Atkin, 2012). This strategy is coherent with the autonomous control operation of CPS, as highlighted in Table 1.1. In this thesis, an embedded system feedback controller's framework is presented, where CPS integration is improved by enabling the trade-off between cyber and physical performances.

1.2 Motivation of the Research

The integration's enhancement is a main characteristic of CPS that makes it different from other systems. Despite that CPS is mostly a high-level system where the physical process is controlled through the network environment with the access of cloud or web, the integration's enhancement can be implemented at the early stage at embedded system level (Lee and Seisha, 2017, Marwedel, 2018; Taha *et al.*, 2021). One way to improve this integration is to incorporate a co-design technique in designing the controller so that both cyber and physical performances can be taken into account in the designing process (Zhu and Sangiovanni-Vincentelli, 2018). Most co-design techniques are applied when the controller is involved in multitask control, where they are implemented on the cyber side, which is in a real time system (RTS) scheduling (Aubrun *et al.* 2013; Zanma *et al*. 2022). Meanwhile, an event-based strategy can be considered as the co-design technique from the physical perspective (Yang *et al.*, 2022).

Event-based PID is one of the co-design techniques that allow a trade-off between the number of control computation iterations and physical performance. Recently, research regarding the use of event-based PID to reduce the computation cost has attracted the interest of researchers (Aranda-Escolástico *et al.*, 2020). It can thus be suggested that the event-based PID can handle the energy consumption of computation for a more effective and efficient system, as stated in Miguel-Escrig and Romero-Pérez (2019). However, the event-based PID suffers from the main drawback of the event-based strategy, which are sticking and limit cycles issues (Cervin and Åström, 2007; Ruiz *et al*., 2014). Sticking response is a phenomenon when the controller stops to update even though the output response is far from the reference point, while limit cycles is an oscillatory response generated at the reference point due to the output error keeps moving toward the limit of the event threshold. Beschi *et al.* (2012a) proposed symmetric send-on-delta (SSOD) event-based PI to address the sticking and limit cycle issues. However, SSOD event-based PI cannot be tuned using existing established tuning methods such as Ziegler-Nichols (Ziegler and Nichols, 1942), Simple Internal Model Control (SIMC) (Skogestad, 2003), and Approximate M-constrained Integral Gain Optimization (AMIGO). This leds to the introduction of various new tuning methods spesifically for SSOD, such as, settling time (ST) tuning (Beschi et al., 2012b; 2014), optimization tuning (Romero and Sanchís, 2018; Miguel *et al.*, 2019), and robust optimization (Ruiz *et al.*, 2017). Nevertheless, it would be very valuable if the well-established tuning rules can be applied directly to the event-based PID controller as various performance purpose and robustness goals can be achieved (Sánchez *et al.*, 2020). Moreover, SSOD event-based requires an extra algorithm to symmetrize the error, which contributed to an additional computation. Even though the main objective of an event-based controller is to reduce computation of control signal, some of the efforts to improve the performance of event-based controller with respect to the original time-triggered controller introduce new computation in the basic algorithm, consequently, increasing the computational cost. For instance, event-based improvement by Durand and Marchand (2009) and Durand *et al.* (2018) introduced an exponential function in the algorithm which is an expensive arithmetic computation function. This study is motivated to further investigate the event-based PID algorithm, in order to have a simpler algorithm that can explicitly apply established tuning rules designed for the continuous controller.

It is well known that the PID controller is able to simplify the control operation and give a good performance in controlling the system, and due to this fact, this controller has been widely used in the industry, especially in industrial process control (Åström and Hägglund, 2006; Bequette, 2019). The advance of technology in control, computing, and communication has had a big impact on industrial process control, where the processes are moving toward autonomous process control. In doing so, the CPS approach should be adopted for controlling the processing plant (Wang *et al.*, 2008). However, due to the huge challenge in CPS, not much work has been done regarding the CPS approach to process control. As a result, it is beneficial if there is a framework that consists of design guidelines on how to implement a CPS in a process control plant. It is also desirable to use co-design event-based PID as a feedback controller for CPS to enhance its integration by allowing a trade-off between cyber and physical performances.

1.3 Problem Statement

The impact of advanced control, computing, and communication technology has greatly benefited the industry. As a result, an industrial process control does not want to miss out on the opportunity to improve its production operational efficiency by implementing these advanced technologies through a CPS approach (Wang *et al.*, 2008). Unfortunately, only a few studies have been conducted to address the challenges of implementing CPS in industrial process control (Isaksson *et al.* 2018). CPS emphasis the integration of cyber and physical elements, where it is possible to be conducted using a co-design technique such as event-based controller (Liu *et al.*, 2022). However, there are still no framework or guideline procedure to utilize the event-based controller as a CPS feedback controller for process control plant.

Event-based PID can be a possible co-design technique for process plant in order to incorporate CPS in controlling the process plant. However, due to the sticking and limit cycles issues, a well-established tuning rule for PID controller in process plant is not suitable for event-based PID (Sánchez et al., 2020). Moreover, most of the efforts in improving the event-based PID will introduce new computation which increase the computational cost. On the other hand, CPS mostly runs on the network environment where the timing imperfections in computing and communication components affect the system performance and reliability. In RTS, control computation is one of the scheduling tasks, thus it will inherit several issues such as delay jitter, task execution time scheduling and task preemption. The variation of input-output delay over the period can deteriorate the control performance and possibly destabilize the system. Hence, to enable event-based PID as a CPS feedback controller, it should be evaluated with the presence of these timing constraints.

In summary, CPS requires a new design methodology to co-design the controller in order to fulfil both cyber and physical objectives. This co-design framework should have a design structure in designing a controller that is able to reduce the computation usage while maintaining physical performance, and the evaluation technique that can facilitate the method to consider timing constrains in CPS. From the above discussion it has clearly shown the potential of event-based PID to be a CPS feedback controller for a process control plant. Therefore, there is a definite need for further research to develop the event-based PID with a simple algorithm and able to address the sticking and limit cycles problems under the presence of network issue.

1.4 Research Objectives

The main aim of this research project is to design a CPS feedback controller that is able to enhance the integration between cyber and physical elements by allowing the trade-off between cyber and physical performances. The objectives of this research are listed as follows:

a. To develop a co-design framework of control and computation load reduction for a CPS. This co-design framework should be able to:

    i. facilitate feedback control design with the specific physical requirement that considers the energy usage of the cyber element.
    ii. address the issue of varying nondeterministic delay (jitter) in network environment.

b. To verify the proposed co-design framework through simulation in the networked environment.

1.5 Scope of the Study

The scope of the overall research is listed as follows:

a. The feedback embedded control system with a delay effect is used as CPS. As the system requires an enhancement on the interaction between cyber and physical parts, the improvement of the interaction is designed at the feedback controller design stage.

b. A CPS based on industrial process plant with a non-critical time constant is considered in this work. Lag, balance and dominant processes are examined, and the controller is designed based on a feedback linear time-invariant (LTI) system.

c. The proposed controller is developed based on a Proportional Integral (PI) feedback controller.

d. The tuning method for the PI controller is based on the first order plus dead time (FOPDT) approximation technique.

e. A MATLAB/Simulink/Truetime environment is considered as the main software used for simulation and experimental tests.

f. An energy saving reduction is estimated to be proportional with the control computational reduction and iteration.

1.6 Contribution of the Research Work

The main contributions from this study are:

a. A new framework for designing an embedded CPS is introduced by using a co-design feedback controller approach to enable a trade-off between control computation reduction and physical performance. The reduction of the control computation will lead to cyber energy saving. The framework consists of the design process, design tool, and verification technique. This new framework can be used to distinguish the design of CPS over other digital control designs.

b. Improvement on algorithm and triggering mechanism for event-based Proportional-Integral (PI) controller namely fixed period algorithm (FPA) and combined triggering mechanisms algorithm (CTMA) are presented. The improved algorithms result in a less computational effort and is able to avoid sticking and limit cycles response.

1.7 Thesis Outline

This thesis is composed of six main chapters, including this introductory chapter. Chapter 1 gives a brief overview of the research background, research motivations, problem statements, research objectives, scopes, and contributions.

Chapter 2 begins with the brief history of CPSs, follows by the review on existing co-design control strategies and event-based control strategies. Then, the literature review is summarised and the research gap is identified.

Chapter 3 presents the methodology of the overall research in achieving all the research objectives. In this chapter, the framework of the co-design feedback controller, plant model, tuning method and evaluation benchmark are explained in detail.

Chapter 4 is divided into two parts. The first part elaborates the proposed and benchmarking of event-based control approaches. The second part presents the results and analysis regarding the trade-off of cyber and physical performances.

Chapter 5 explains and presents the evaluation techniques for the proposed method under the effect of the network environment. Several tests including constant and time-varying delays are carefully conducted. Then the results are presented along with the analysis.

In Chapter 6, the conclusion and contributions of the research are presented. The recommendations of the possible future work and direction are also covered in this chapter.

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LIST OF PUBLICATIONS

Journal

1. Md Yusop, N., Mamat, R, (2021), ‘Improved Event-Based PI Controller for Limit Cycles Avoidance’. *International Journal of Integrated Engineering* 13(4),63-76 (Scopus indexed).

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2. Md Yusop, N., Mamat, R, (2020), ‘Analysis of Event-Based PI Controller and Some Proposed Improvements’. In *2020 IEEE International Conference on Automatic Control and Intelligent Systems (I2CACIS 2020)*, Shah Alam, Malaysia, 170-175 (Scopus indexed).