LOGICAL CONSENSUS CONTROL FOR A SMART WATER DISTRIBUTION SYSTEM

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DEDICATION

This thesis is dedicated to my husband, who sacrificed almost everything left in his life for me to complete my study, also to my son, my M.Phil. baby, who grew up throughout my journey. I dedicated this thesis to my father and mother, who courage me to achieve the best kind of knowledge.

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ABSTRACT

Urban water distribution systems (WDS) should be designed not only for the safe provision of services but should also be resilient to unexpected threats that may lead to catastrophic system failure. Outdated facilities, water shortage, limited water resources, global population growth, industrial revolutions, global warming, and climate changes including flash floods and prolonged droughts are the potential challenges to the urban WDS. These challenges urge many countries to strategize and seek innovative ideas to secure a sustainable supply of water. With the emergence of the Internet of Things (IoT), cloud computing, big data analytic, and smart sensors, massive real-time information can be remotely collected and monitored. Capability in utilizing data analytics in real-time operation promises greater efficiency in WDS management. Thus, there is an increasing need to leverage IoT-based technologies to ensure the WDS infrastructure and operation are sustainable and resilient. Therefore, the present study develops an automated real-time decision-making mechanism for a smart WDS. A logical consensus algorithm is developed to coordinate multiple sensors, controllers, and actuators by utilizing real-time information on the overall system. The logical consensus is a binary triggered detection system that is suitable for WDS applications that requires opening and closing valves to optimize the normal operation and to react efficiently upon failure occurrence. The framework proposed is based on the algebraic graph theory, which consists of visibility, communication, and reachability matrices and the iteration rules designed based on the cellular automata (CA). The CA is a dynamic structure of a discrete computation model that is fundamentally based on local interaction and computation. Two different physical WDS layouts are considered; the basic combined configuration and the actual Balok water supply layout which represent multiple combinations of branch and grid configurations. The proposed algorithm is designed and simulated using MATLAB programming and mathematical computing software. To analytically validate the convergence achieved in simulation, the reachability analysis is conducted using Hamiltonian Cycle and full rank matrix. The simulation result shows that the proposed algorithm has a significant advantage in terms of convergence time by converging 45% faster compared to the benchmark algorithm which is more computational demand due to the combination of several rules. Based on the developed algorithm, a large number of devices including valves can be activated and de-activated simultaneously. The implementation of the CA in the logical consensus control algorithm has increased the sustainability of WDS operation, particularly at a partial operation. The results of this study further broaden the application of logical consensus with CA in a control system, and most importantly, the developed algorithm will be useful to the development of the next generation of resilient and efficient WDS.

ABSTRAK

Sistem pengagihan air (WDS) bandar harus dirancang bukan hanya untuk penyediaan perkhidmatan yang selamat tetapi juga harus mempunyai ketahanan terhadap ancaman yang tidak dijangka. Kemudahan yang ketinggalan zaman, kekurangan air, sumber air yang terhad, pertumbuhan populasi global, revolusi perindustrian, pemanasan global, dan perubahan iklim termasuk banjir kilat juga kemarau yang berpanjangan adalah potensi cabaran kepada WDS terkini. Cabaran ini menggesa banyak negara untuk menyusun strategi dan mencari idea inovatif untuk mendapatkan bekalan air yang mampan. Dengan munculnya Internet Pelbagai Benda (IoT), pengkomputeran awan, data raya beranalisis, dan sensor pintar, maklumat masa nyata yang besar dapat dikumpulkan dan dipantau dari jauh. Keupayaan dalam menggunakan analisis data dalam operasi masa nyata menjanjikan kecekapan yang lebih besar dalam pengurusan WDS. Oleh itu, terdapat peningkatan keperluan untuk memanfaatkan teknologi berdasarkan IoT dalam memastikan infrastruktur dan operasi WDS dapat bertahan dan bingkas. Oleh itu, kajian ini membangunkan mekanisme membuat keputusan masa nyata berautomatik bagi WDS pintar. Algoritma konsensus logik dibangunkan untuk mengkoordinasikan pelbagai sensor, pengawal, dan penggerak dengan menggunakan maklumat masa nyata pada keseluruhan sistem. Konsensus logik adalah sistem pengesanan yang dicetuskan binari yang sesuai untuk aplikasi WDS yang memerlukan pembukaan dan penutupan injap untuk mengoptimumkan operasi normal dan bertindak balas dengan cekap apabila berlaku kegagalan. Kerangka yang dicadangkan berdasarkan teori grafik aljabar, yang terdiri dari matriks kebolehlihatan, komunikasi, dan jangkauan dan peraturan lelaran yang direkabentuk berdasarkan automata bersel (CA). CA adalah struktur dinamik kepada model pengiraan diskret yang pada asasnya berdasarkan interaksi dan pengiraan tempatan. Dua susunatur fizikal WDS yang berbeza dipertimbangkan; tatarajah gabungan asas dan susunatur bekalan air Balok sebenar yang mewakili gabungan pelbagai tatarajah cawangan dan grid. Algoritma cadangan tersebut direka dan diselakukan menggunakan pengaturcaraan dan perisian pengkomputeran matematik MATLAB. Untuk mengesahkan penumpuan beranalisis yang dicapai dalam simulasi, analisis jangkauan dijalankan menggunakan Kitaran Hamiltonian dan matriks peringkat penuh. Hasil simulasi menunjukkan bahawa algoritma yang dicadangkan mempunyai kelebihan yang ketara dari segi masa penumpuan dengan menumpu 45% lebih cepat berbanding algoritma penanda aras yang lebih permintaan pengiraan kerana gabungan beberapa peraturan. Hasil algoritma yang dibangunkan menunjukkan bahawa dalam kebanyakan kes, topologi rangkaian dengan lebih banyak unsur bukan sifar dalam matriks kebolehlihatan mempunyai kelebihan yang signifikan dari segi masa penumpuan. Berdasarkan algoritma yang dibangunkan, sebilangan besar peranti termasuk injap dapat diaktifkan dan dinyahaktifkan secara serentak. Pelaksanaan CA dalam algoritma kawalan konsensus logik telah meningkatkan kebolehtahanan operasi WDS terutamanya pada kendalian separa. Hasil kajian ini memperluas penerapan konsensus logik dengan CA dalam sistem kawalan, dan yang paling penting, algoritma yang dibangunkan adalah berguna untuk perkembangan WDS generasi berikutnya yang berdaya tahan dan cekap.

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LIST OF ABBREVIATIONS

UTM	-	Universiti Teknologi Malaysia
WDS	-	Water Distribution System
PUB	-	Public Utilities Board
SWG	-	Smart Water Grid
IoT	-	Internet of Things
SWGS	-	Smart Water Grid Systems
ICT	-	Information and Communication Technology
DCS	-	Distributed Control System
CA	-	Cellular Automata
HC	-	Hamiltonian Cycle
NMAS	-	Networked Multi Agent System
SIWW	-	Singapore International Water Week
WEF	-	World Economic Forum
ADB	-	Asian Development Bank
MPC	-	model predictive control
NRW	-	Non-Revenue Water
UAVs	-	Unmanned Aerial Vehicles
WSN	-	Wireless Sensor Network
IDS	-	Intrusion Detection System
AMR	-	Automatic Meter Reading
EU	-	European Union
USA	-	United States of America
NSWG	-	National Smart Water Grid
SEQ	-	South East Queensland
ECA	-	Elementary Cellular Automata
1-D	-	one-dimensional
2-D	-	two-dimensional
VLSI	-	very large scale integration
LUT	-	look-up table

LIST OF SYMBOLS

$\mathcal{L}$	-	lattice
$c_{N_{\mathcal{L}}}$	-	cells of lattice
$N_{\mathcal{L}}$	-	number of cells on lattice
$\mathcal{N}$	-	neighborhood
A	-	characteristic polynomials
t	-	time
$\mathbb{T}$	-	characteristic matrix of transition update rule
f	-	function
m	-	events
$\mathscr{f}$	-	decisions
X_i	-	binary vector state
i	-	local agent
j	-	neighboring agent
Y_i	-	output decision vector
C	-	communication matrix
V_j	-	visibility matrix
n	-	number of agents
u_j	-	input event
R_j	-	reachability matrix
I_j	-	column of reachability matrix
N_i	-	agent
f_{th}	-	flowrate threshold value
$f_{i,j}$	-	flowrate of water flow from i to j
d	-	dimension of lattice
$\mathbb{R}$	-	real number
$\mathbb{B}$	-	element of binary
$\mathcal{S}$	-	set of cells' states
s_t	-	state of cells
r	-	radius

k	-	size of neighborhood
I	-	identity matrix
s_d	-	desired matrix
$\mathcal{U}$	-	set of control inputs
u_t	-	control input in term of time steps
ω	-	sub-domain region
T_{FINAL}	-	final time step
c_{left}	-	cell located on the left side before the sub-region
c_{right}	-	cell located on the right side after the sub-region
$\mathcal{L}_p$	-	Lattice of sub-region
$\mathcal{F}$	-	global additive transition function
$\mathcal{G}$	-	global control function
s_0	-	initial state
$s_{T_{FINAL}}$	-	final state

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter provides an introductory overview on the main aspects considered throughout the thesis. The background of the problem is briefly discussed on water utilities, water distribution system (WDS) and the importance to implement information and communications technologies (ICT) on WDS in Section 1.2 and it is then narrowed down into a more specific problem statement to clarify the needs and motivations of the thesis as in Section 1.3. The research objectives in Section 1.4 are constructed to reflect the problem statements. The scopes of research are mapped in Section 1.5 to set the boundaries of the study followed by significance of study in Section 1.6 to signify how the proposed algorithm will improve the scientific knowledge and capability. Finally, this chapter is descriptively concluded in Section 1.7 by laying out the skeleton of the thesis.

1.2 Problem Background

The work in [1] has reported that the biggest threat to modern civilization is water shortage, caused by urbanization. The increasing population and effect of global warming causing bizarre weather patterns had contributed significantly towards the water distribution problem. Specifically, in ASEAN countries, this problem is amplified by the WDS design and facilities that are outdated and inefficient. The steady increment of the population in these countries means that these facilities are stretched to the limit causing frequent failure and disruptions, resulting in poor performance [2].

According to Singapore's National Water Agency, Public Utilities Board (PUB), upgrading WDS to be resilient towards disruption is one of the key points of the discussion in digitalizing water. Various national plans have been addressed to enhance the sustainability and resilience of the water supply including developing a smart water grid (SWG). To help the water utilities to operate more efficiently with limited water resources during the disruption, integrated solutions using the Internet of Things (IoT) is suggested in [3]. With sensors are getting cheaper by the advancement in electronics, the affordable integrated system can be easily developed and deployed to get real-time information to enhance water management and overall operations [4].

Even though there are significant efforts in developing and enhancing the execution of water conveyance particularly amid facilities disruption, the majority of them did not incorporate advanced technologies such as IoT. The key challenge in implementing the IoT for WDS is the coordination and cooperation among various units such as sensors, controllers, and actuators. However, manipulation of the vast information available through the application of IoT requires the application of control system design specifically for achieving efficient operation through consensus while minimizing the impacts of water supply disruption to customers.

One of the most crucial parts of the Smart Water Grid System (SWGS) is to integrate ICT into WDS management [5], which involves a combination of numerous sensors, actuators, meters, tanks, and analytic tools that replicates a water supply facility representing a distributed control system (DCS). In the present study, the water distribution is governed by consensus-based control to establish a smart WDS. The network communication topology with the ability to disseminate information throughout the system will be configured to limit the aggregate impact of unplanned disruption and allow the maintenance work to be performed simultaneously. The primary part of the control is to coordinate actions based on the state of the available resources, the sensing information, the network topology, and the goals of the system (consensus).

The designed control system decision is versatile and can be overridden by the human operator to ensure flexibility. The performance of the developed system was demonstrated in a simulation using a multiple water tanks system. This study is expected to be able to help in developing a control system that is suitable for water supply application, not only within Malaysia but also could be shared and adapted to other regional needs.

1.3 Problem Statement

The World Economic Forum 2016 stated that water crisis is one of the global biggest threats [4]. The increasing population and effect of global warming causing a bizarre weather pattern have contributed significantly towards the water distribution problems. Specifically, in ASEAN countries, this problem is amplified by the water distribution design and facilities that are outdated and inefficient [2]. With the motivation to provide water sustainability for the communities and guarantee access to drinking water, this thesis binds the problem by providing the solution to upgrade the WDS facility into a SWGS to offer more reliability for the system's operation.

In the new paradigm for WDS, ICT is being implemented to demonstrate the comprehensive planning and implementation tool to manage and develop the water resources in a way that balances social and economic needs which leads to a SWGS with a goal to sustain adequate water supply for urban areas [6]. The motivation of this study is the digitalizing water roadmap of Singapore where the advancements in digital and information communications technologies were transforming the global landscape, and could offer water utilities new methods of enhancing their productivity and efficiency in planning, operations and service delivery without greatly impacting costs. SWGS is designed to achieve three different tasks simultaneously; to modernize the WDS with smart devices, to educate the consumers on their water usage, and also to ensure the security of the water resources which have been widely conducted in Singapore, Australia, European Union countries, United States of America, and South Korea. By exploiting advantages of advanced communication technologies nowadays, the first task is more appropriate to be studied. Urban WDS structures with optimal performance can be planned by using these technologies, ensuring the system's efficiency and stability.

With the motivation to implement ICT on WDS with fault detection mechanism, the work in [7] first conducted a simulation study that served as our benchmark. The findings, however, are presented without comprehensive analytical validation [7]. Furthermore, the network topology planning is not investigated. Hence, the primary goal of this study is to design a generic framework of logical consensus control for WDS that is both analytically proven and extensible to other Networked Multi-Agent System (NMAS) applications.

1.4 Research Objectives

The objectives of the research are:

(a) To develop logical consensus control algorithm to facilitate WDS real-time decision-making based on network communication topology regardless of physical configuration.

(b) To provide analytical validation to the developed logical consensus control.

1.5 Scope of Work

Based on objectives, the general goal of this research is to bring the vast potential of advanced technologies and theoretical knowledge of consensus-based control into WDS applications. With this mindset, the entire research process has been centered on developing a consensus-based control strategy for a smart WDS.

In the employed smart WDS, a single unit of a water tank system that is independently equipped with a tank, valve, withdrawal line, and network communication is considered as an agent. However, this study is constructed with the limitation on the geometrical structures of WDS including the dynamic, volume, distance, and dimension. In this case, the geometrical structures are neglected so that it will be easily expanded besides increasing its flexibility. The study intended to develop the consensus-based control that is universal, which applies to homogeneous or heterogeneous WDS dynamics and can be easily extended to any arbitrary WDS configurations. The proposed algorithm is developed based on communication matrix, visibility matrix, and reachability matrices properties related to algebraic graph theory and iteration algorithm based on simple computation called cellular automata (CA). Specifically, the implementation of CA in this study involves a deterministic linear CA considering null and periodic boundaries with additive update rules. The proposed algorithm is validated using reachability analysis which involves Hamiltonian Cycle (HC) and full rank matrix to verify the system's reachability. The present study considers two types of WDS configurations; basic combined configuration and complex combined configuration from the actual layout available in [8]. The proposed algorithm is designed, simulated, and analyzed using m-file coding in MATLAB.

1.6 Significance of Research Work

Water availability is gradually stressed by the increasing global population growth, industrial revolutions, global warming, and climate changes which can lead to water shortage. With the outdated and inefficient WDS designs and facilities, most countries are in need to improve WDS scarcity to ensure water sustainability for the communities and guarantee access to drinking water. Integrating advanced ICT with advanced decision-making and control algorithms in WDS operation and management is one way to attain this goal.

To date, no comprehensive work has been conducted for consensus-based control in smart WDS with the utilization of logical inputs and CA algorithms. The developed algorithm is generic, simple, and does not rely on the dynamic of agents.

Furthermore, the algorithm proposed is flexible and not limited to WDS application but applies to any NMAS that require coordination or decision-making facility at a partial operation due to fault occurrence.

1.7 Organization of Thesis

Chapter 1 provides a brief overview of the research topic. Generally, the research is described with the background of the study, followed by a detailed explanation of problem statements, objectives, limitations, and significance of the research.

Chapter 2 reviews significant works on consensus-based control strategies that have been accomplished over the past few decades. The literature is grouped into five types of consensus including average consensus, min-max consensus, consensus function, logical consensus, and external tracking consensus. Then, the literature describes the advancement and classification of WDS configurations. This chapter also presents detailed literature on CA which has to be the main part of developing the logical consensus control algorithm.

Chapter 3 illustrates the systematic execution of this work. The methodology will include the workflow of the entire research. The framework of this study is also presented in this chapter. A few definitions, theorems, and examples are included in this chapter to enhance the understanding of this study.

Chapter 4 presents the results of the work done in parallel directions as in Chapter 3 to achieve the objectives. With the ambitious goals, the understanding of this study is grasped through simulations beforehand. The work done will be validated through a series of theoretical analysis to justify the results obtained.

The final chapter sums up the whole idea of the research topic and provides the means to develop this extremely important study on consensus-based control strategy, as it is essential to meet the plans for future directions

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LIST OF PUBLICATIONS

Indexed Conference Proceedings

1. N.H.M. Yusof, N.A.M. Subha, and S.M. Hussin, "Development of Modular Networked Multi Process Control System: Low-Cost NMS Simulator," *IEEE International Conference on Automatic Control and Intelligent Systems*, pp. 24-28, 2018. (Published – IEEE)
2. N.H.M. Yusof, N.A.M. Subha, F.S. Ismail, and N. Hamzah, "Logical Consensus-based Control for Water Distribution System with Physical Faults," *IEEE International Conference on System Engineering and Technology*, pp. 108-112, 2020. (Published – IEEE)
3. N.H.M. Yusof, N.A.M. Subha, N. Hamzah, F.S. Ismail, M.A.M. Basri, and A. Ahmad, "Controllability Analysis of Convergence on Water Distribution System Architecture with Fault using Cellular Automata Sequence," *International Conference on Mechanical Engineering Research*, 2022. (Presented – Scopus)

Non-Indexed Conference Proceedings

4. N.H.M. Yusof, N.A.M. Subha, F.S. Ismail, N. Hamzah, M.A.M. Basri, M.A. Shamsudin, and N.M. Nordin, "A Generic Framework of Agent-based Water Distribution System Architecture with Physical Fault using Cellular Automata Sequence," *Proceedings of International Conference on Intelligent & Interactive Computing*, 2021. (Published)

Book Chapters

5. N.H.M. Yusof, N.A.M. Subha, F.S. Ismail, and M.A.M Basri, "Chapter 8: Modelling of Water Distribution System," in *Studies in Control and System Automation*, UTM Press, 2019. (Published)
6. N.H.M. Yusof, N.A.M. Subha, F.S. Ismail, and N. Hamzah, "Chapter 9: Distributed Logical Consensus Protocols for Water Distribution System with Faults," in *Decision for Control and Mechatronics Engineering in Multiple Applications*, UTM Press, 2021. (Accepted)