BLACK-BOX MODELING AND ADAPTIVE CONTROL OF HYBRID THERMOELECTRIC REFRIGERATOR SYSTEMS

by

MOHD SAIFIZI BIN SAIDON

(1340610910)

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UNIVERSITI MALAYSIA PERLIS

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LIST OF ABBREVIATIONS

ARMAX	AutoRegressive Moving Average with eXogenous
ARX	AutoRegressive with eXogenous
ATAGI	Australian Technical Advisory Group on Immunization
DAQ	Data Acquisition
DC	Direct Current
GMVC	Generalized Minimum Variance Controller
GPC	Generalized Predictive Controller
H-TER	Hybrid Thermoelectric Refrigerator
IGMVC	Incremental Generalized Minimum Variance Controller
IO	Input-Output
MRAC	Model reference adaptive controller
PI	Proportional-integral
PID	Proportional-integral-derivative
PRBS	Pseudo Random Binary Sequence
PWM	Pulse Width Modulation
RELS	Recursive Extended Least Squares
RLS	Recursive Least Squares
RTD	Resistance Temperature Detector
SSR	Solid State Relay
STC	self-tuning controllers
TEM	Thermoelectric Module
WHO	World Health Organization

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LIST OF SYMBOLS

T	temperature
ρ	density
κ	thermal conductivity
γ	electrical resistivity
τ	Thompson coefficient
A_T	area of TEM
I	current
T_c	cold surface temperature
T_h	hot surface temperature
T_o	temperature of the cooling object
T_a	ambient temperature
R_{oc}	thermal resistant between the cooling object with TEM's cold side
R_{ha}	thermal resistant of the heat sink
Q_{oc}	heat pumped at cold object
Q_{ha}	energy consumption required by ambient temperature
R_e	device electrical resistance
C_o	capacitances of the system/object
S_e	device Seebeck voltage
Q_o	thermal load
R_T	resistance temperature
R_0	nominal resistance
U, u	input
Y, y	output

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T_c	time constant
T_s	sampling time
F_a	filter parameter
$A(z^{-1})$	polynomial z^{-1}
$B(z^{-1})$	polynomial in z^{-1}
$C(z^{-1})$	model polynomial in z^{-1}
$D(z^{-1})$	model polynomial in z^{-1}
$L(z^{-1})$	model polynomial in z^{-1}
$e(t)$	noise/error
$a_{1,}, a_2, ...a_{na}$	parameter coefficient
$b_{0,}, b_1, ...b_{nb}$	parameter coefficient
z	unit forward shift operator; z-transform argrument
$\hat{\boldsymbol{\theta}}(t\text{-}1)$	previous data information
$\hat{y}(t)$	current output estimation
$\hat{e}(t)$	modelling error
$\varepsilon(t)$	prediction error
$\eta(t)$	a posteriori prediction error
$J(\theta)$	least squares function
K	correcting vector
K_p	proportional gain
T_i	integral time
T_d	derivative time
K_{IO}	output change over input change
d_T	time delay
$\xi(t)$	white noise

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ς	nominal constant
$\psi(t)$	auxiliary output
$P(z^{-1})$	output weighting
$R(z^{-1})$	set point/reference weighting
$S(z^{-1})$	control effort weighting
θ	parameter vector
$\boldsymbol{\theta}(t)$	time varying parameter vector
$\hat{\boldsymbol{\theta}}(t)$	estimated parameter vector based on data available at time t
$\boldsymbol{x}(t)$	regression (or data) vector
$\boldsymbol{\varphi}(t)$	regression vector in RELS
$\boldsymbol{X}, \boldsymbol{X}(t)$	stacked data vectors (matrix)
$\boldsymbol{P}(t)$	covariance matrix in RLS and RELS
k	time delay (discrete)
β	model correction term
J	sum of squares of errors/cost function
$G(z^{-1})$	controller polynomial
$F(z^{-1})$	controller polynomial
$E(z^{-1})$	controller polynomial
$\Gamma(z^{-1})$	controller polynomial
N_{p1}	minimum horizon cost
N_{p2}	maximum horizon cost
N_u	control horizon
$\Delta u(t+j)$	increment control input of a system
λ_f	forgetting factor
λ	weightage for incremental of control signal

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Δ	difference operator $\left(1-z^{-1}\right)$
$\Delta \boldsymbol{u}$	vector of control increment

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Pemodelan Kotak-Hitam dan Kawalan Suai Sistem Peti Sejuk Hibrid Elektrik Haba

ABSTRAK

Pembawa vaksin telah digunakan untuk mengekalkan suhu dalam 2-8°C. Walaupun, pembawa vaksin tidak berfungsi dengan baik yang boleh mendedahkan vaksin kepada suhu beku. Peti Sejuk Hibrid Elektrik Haba dibangunkan untuk pengangkutan vaksin sensitive ke hospital pada suhu yang dikawal tepat. Peti sejuk ini menggunakan pam elektrik haba udara-ke-udara dan langsung. Tugasan ini melaporkan pemodelan dan kajian kawalan yang dijalankan untuk sistem. Bahan bekas (aluminuim dan keluli tahan karat) dari jenis yang berbeza digunakan dan perbandingan diantara mereka dianalisa. Sistem ini tidak lelurus dan mempamerkan parameter model yang berubah-ubah, dan masa mati. Objektif dalam kajian ini adalah untuk menyiasat strategi kawalan yang berasaskan kepada pengetahuan loji bukan keutamaan namun membenarkan penyesuaian berterusan untuk pengawal kepada sistem dinamik yang berubah-ubah. Malah, beban penyejukan yang pelbagai juga menyebabkan pengurangan kecekapan peti sejuk termasuk masukkan turun naik paras arus yang disebabkan oleh prestasi elektronik komponen dan keadaan operasi modul thermoelektrik pada hujung sejuk dan panas yang pelbagai sepanjang masa. Oleh itu sistem kawalan suai dipertimbangkan menangani masalah yang dinyatakan di atas. Pendekatan pemodelan kotak-hitam dipilih kerana ini diperlukan untuk perlaksanaan pengawal suai. Sistem H-TER telah dikenal pasti menggunakan kedua-dua kaedah Rekursi Kuasa Dua Terkecil (RLS) dan Rekursi Dipanjangkan Kuasa Dua (RELS). Memandangkan RELS telah terbukti memberi anggaran yang berat sebelah bagi data yang ditapis dan anggaran penumpuan perlahan bagi data yang tidak ditapis, nilai didapati daripada RLS telah dipilih untuk model ini. Model tertetib kedua sistem H-TER I dan H-TER II didapati secukupnya mewakili sistem tersebut kerana ia member padanan terbaik 0.0009 dan 0.0007 masing-masing, dengan membuat tertib keempat menjadi tidak signifikan. Prosedur pengesahan menggunakan model tertib kedua untuk penilaian dalam talian, menunjukkan bahawa model ini sememangnya perwakilan yang baik bagi sistem H-TER. Pengawal On-Off dan PI adalah yang biasa digunakan dalam sistem penjana elektrik haba untuk sistem ini diaplikasikan sebagai kajian kes. Pengawal PI menunjukkan prestasi yang lebih baik daripada pengawal On-Off dari segi ralat keadaan mantap. Tetapi pengawal PI tidak memberikan prestasi yang baik kepada masukkan lelurus sesecebis pengaturan serta merta kerana parameter pengawal tidak dapat menyesuaikan dengan sewajarnya. Dua pendekatan utama penyesuaian kawalan talaan-diri iaitu Pengawal Teritlak Minimum Varian (GMVC) dan Pengawal Tokokan Teritlak Minimum Varian (IGMVC). Kaedah IGMVC menghasilkan prestasi yang terbaik dari segi ralat keadaan mantap kurang daripada ±0.15°C. Walau bagaimanapun, kedua-dua algoritma memenuhi keperluan keluaran sistem H-TER, yang seharusnya sekitar 4°C, dengan kehadiran lelurus sesecebis masukkan. Kerana pemodelan sistem H-TER melibatkan masa mati, disebabkan keadaan muatan yang berbeza, satu Teritlak Ramalan Pengawal (GPC) juga dilaksanakan bagi menangani perkara ini. Menggunakan GPC ini, ia didapati bahawa sistem H-TER sentiasa stabil walaupun dengan kehadiran lelurus sesecebis masukkan dari segi mengesan dan mengawal. Ia melihat bahawa prestasi pengawal GPC penjejakan dan pengaturan adalah lebih baik daripada GMVC dan IGMVC.

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Black-Box Modeling and Adaptive Control of Hybrid Thermoelectric Refrigerator Systems

ABSTRACT

Vaccines carrier has been used to keep the temperature within 2–8°C. However, a poorly functioning vaccines carrier may expose the vaccines to freezing temperatures. Hybrid Thermoelectric Refrigerator (H-TER) systems are developed in order to transport sensitive vaccines to hospitals at accurate controlled temperature. The refrigerator use air-to-air and direct thermoelectric heat pumps. This work reports on modeling and control studies carried out for H-TER systems that can control low temperature accurately. Different type of material containers (aluminium and stainless steel) is used and comparisons between them are analyzed. The systems are nonlinear and exhibits varying model parameters and dead-time. The objective of the study is to investigate control strategies that are based on non-*priori* plant knowledge and yet allowing for continuous adaptations of the controller to changing system dynamics. In fact, the various cooling load also causes a reduction of refrigerator efficiency including the fluctuation of imposed current level due to electronic component performance and varied operating condition of thermoelectric module on cold and hot ends against time. Thus an adaptive control system is considered to handle the problems that are stipulated above. A black box modeling approach is chosen since this is needed for the implementation of adaptive controllers. The H-TER systems have been identified using both Recursive Least Squares (RLS) and Recursive Extended Least Squares (RELS) methods. Since RELS has shown to give biased estimates for filtered data and slow convergence estimates for unfiltered data, RLS has been chosen for the model as its give a better representation of the systems. A second order model of H-TER I and H-TER II systems are found to adequately represent the system as it give best fit of 0.0009 and 0.0007 respectively which made the fourth order to be insignificant for implementation. Validation procedures using second order model for online estimation, show that the model is indeed a good representation of the H-TER systems. On-Off and PI controllers are the commonly used in thermoelectric system is applied to this system as case studies. PI controller shows better performance over On-Off controller in term of steady state error. However, the PI controller does not provide a good piecewise linear input regulation performance instantaneously because the controller parameters could not adapt accordingly. Two main adaptive self-tuning control approaches i.e. Generalized Minimum Variance Controller (GMVC) and Incremental Generalize Minimum Variance Controller (IGMVC) with varying control weighting parameters are implemented. The IGMVC method produces the best performance in terms of steady state error less than ±0.15°C. However, both algorithms satisfy the requirement of the H-TER systems output, which should be around 4°C, in the presence of piecewise linear input. As modeling of the H-TER systems involve time delay, due to different loading condition, a Generalize Predictive Controller (GPC) is also implemented to address this matter. Using the GPC, it is observed that the H-TER systems are always stable even in the presence of piecewise linear input in term of tracking and regulating. It is observe that the performance of the GPC controller tracking and regulating is superior to GMVC and IGMVC.

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CHAPTER 1

INTRODUCTION

1.1 Overview

It is a common fact that vaccines are very sensitive to heat and light, with some types of vaccines should not even be frozen. Thus, vaccines need to be stored at an appropriate temperature range from the time of manufacture until the time of use. Vaccines will lose its optimal potential, if not stored or transported in an appropriate environment temperature or exposure to light. Maintaining appropriate storage temperature for vaccines is not an easy task. Failure to do so can be disastrous to the user. Vaccine must be kept in optimum condition to achieve effective immunization to the user.

Among the key element for improving the quality of immunization programs is to ensure the management level at cold chain and vaccine logistics is in good condition. The cold chain is a system of transport and storage of vaccines at controlled temperatures ranging from 2°C to 8°C as shown in Fig 1.1. This temperature range has been chosen by the World Health Organization (WHO), and has been adopted by the Australian Technical Advisory Group on Immunization (ATAGI) as their manual for vaccine protection against damage by heat and cold (WHO, 2011). Cold chain is a system that starts from the time vaccines are produced, then continues through to the

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