Faculty of Electrical Engineering

OPTIMIZED FUZZY LOGIC SLIDING MODE CONTROL WITH PROPORTIONAL-INTEGRAL-DERIVATIVE FOR AN ELECTROHYDRAULIC ACTUATOR SYSTEM

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DECLARATION

I declare that this thesis entitled "Optimized Fuzzy Logic Sliding Mode Control with Proportional-Integral-Derivative for an Electrohydraulic Actuator 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 the candidature of any other degree.

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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Doctor of Philosophy.

Signature	:	………………………………………………
Supervisor's Name	:	Associate Professor Dr. Rozaimi Ghazali
Date	:	30/5/2023

DEDICATION

To my lovely wife, Nur Safiyah Mohamad Adib for her tolerance, inspiration and constant support over the years.

To my beloved children, Muhamad Fayyadh Alqushayyi and Muhamad Faheem Alfateh for creation my life productive and pleasant.

ABSTRACT

The electrohydraulic actuator (EHA) system generates a trajectory by transferring high force densities in the form of pressurized fluid flows to a hydraulic actuator. Moreover, the sliding mode control (SMC) approach has been discovered as a potential method for the EHA trajectory tracking control system. However, high-frequency proportional valve activity has occurred during the practical application of the conventional SMC approach, resulting in tracking performance degradation. Furthermore, a preferable SMC sliding surface design is necessary to improve the precision of trajectory tracking performance, and the SMC designs involve complicated procedure and mathematical formulations. Therefore, this thesis proposes an optimized fuzzy logic (FL) SMC with a proportional-integral-derivative (PID) structure for trajectory tracking control in an EHA system. The proposed control strategy was designed with the switching function modification based on an FL approach in the conventional SMC algorithm called FLSMC. A particle swarm optimization (PSO) algorithm was implemented as the FLSMC design involves a complicated procedure and mathematical formulations to obtain the optimal value of the designed control variables. By adopting the same design concept, the conventional SMC approach was developed for performance comparisons. Furthermore, in an attempt to achieve the objectives of precise trajectory tracking control, a hybrid control structure of FLSMC and PID feedback control (FLSMCPID) is proposed and implemented. Due to the difficulty of concurrent hybrid design, the PSO algorithm was employed to determine the optimal control variables value. For performance comparisons with the proposed hybrid control strategy, a hybrid conventional SMC and PID feedback control (SMCPID) was established by using the same design concept. Simulations utilizing a linear EHA system model obtained using the grey-box identification approach and experimentation on an EHA system workbench for various trajectories and under the consequences of variation in supply pressure were conducted to evaluate the performance of the proposed control strategies. A linear type actuation of the EHA system using a single-ended cylinder controlled by a proportional valve was considered in the experimental design. The simulation and experimental results demonstrate that higher effectiveness, precision, and robustness were achieved by the EHA system with the FLSMC and FLSMCPID as compared to the established conventional SMC and SMCPID approaches, respectively. Moreover, the experimental results verified that the EHA system with the FLSMCPID achieved 82.1%, 78.9%, 94.8%, and 88.8% improvement in the precision tracking control for 0.25 Hz sinusoidal, multi-sinusoidal, point-to-point, and chaotic trajectories, respectively, and enhanced the robustness by 33.3% compared to the FLSMC control strategy. It is envisaged that the proposed FLSMC and FLSMCPID control strategies can be utilized for effective, precise, and robust tracking control of various EHA systems.

KAWALAN MOD GELONGSOR LOGIK KABUR YANG DIOPTIMUMKAN DENGAN BERKADARAN-KAMIRAN-TERBITAN UNTUK SISTEM PENGGERAK ELEKTROHIDRAULIK

ABSTRAK

Sistem penggerak elektrohidraulik (EHA) menjana trajektori dengan memindahkan ketumpatan daya tinggi dalam bentuk aliran bendalir bertekanan ke penggerak hidraulik. Selain itu, pendekatan kawalan mod gelongsor (SMC) telah ditemui sebagai kaedah yang berpotensi untuk sistem kawalan pengesanan trajektori EHA. Walau bagaimanapun, aktiviti injap berkadar frekuensi tinggi telah berlaku semasa aplikasi praktikal pendekatan SMC konvensional, mengakibatkan kemerosotan prestasi pengesanan. Tambahan pula, reka bentuk permukaan gelongsor SMC yang lebih baik adalah perlu untuk meningkatkan ketepatan prestasi pengesanan trajektori, dan reka bentuk SMC melibatkan prosedur yang rumit dan rumusan matematik. Oleh itu, tesis ini mencadangkan SMC logik kabur (FL) yang dioptimumkan dengan struktur berkadaran-kamiran-terbitan (PID) untuk kawalan pengesanan trajektori dalam sistem EHA. Strategi kawalan yang dicadangkan telah direka bentuk berdasarkan pengubahsuaian fungsi pensuisan pendekatan FL dalam algoritma SMC konvensional yang dipanggil FLSMC. Algoritma pengoptimuman kawanan zarah (PSO) telah dilaksanakan kerana reka bentuk FLSMC melibatkan prosedur dan rumusan matematik yang rumit untuk mendapatkan nilai optimum pembolehubah kawalan yang direka bentuk. Dengan menggunakan konsep reka bentuk yang sama, pendekatan SMC konvensional telah dibangunkan untuk perbandingan prestasi. Tambahan pula, dalam usaha untuk mencapai objektif kawalan pengesanan trajektori yang tepat, struktur kawalan hibrid FLSMC dan kawalan maklum balas PID (FLSMCPID) dicadangkan dan dilaksanakan. Disebabkan oleh kesukaran reka bentuk hibrid serentak, algoritma PSO telah digunakan untuk menentukan nilai pembolehubah kawalan yang optimum. Untuk perbandingan prestasi dengan strategi kawalan hibrid yang dicadangkan, kawalan maklum balas SMC konvensional dan PID (SMCPID) hibrid telah dibangunkan dengan menggunakan konsep reka bentuk yang sama. Simulasi menggunakan model sistem EHA linear yang diperoleh menggunakan pendekatan pengenalan kotak kelabu dan eksperimen pada meja kerja sistem EHA untuk pelbagai trajektori dan di bawah akibat variasi dalam tekanan bekalan telah dijalankan untuk menilai prestasi strategi kawalan yang dicadangkan. Penggerakan jenis linear sistem EHA menggunakan silinder hujung tunggal yang dikawal oleh injap berkadar telah dipertimbangkan dalam reka bentuk eksperimen. Hasil simulasi dan eksperimen menunjukkan bahawa keberkesanan, ketepatan dan keteguhan yang lebih tinggi telah dicapai oleh sistem EHA dengan FLSMC dan FLSMCPID berbanding dengan pendekatan SMC dan SMCPID konvensional yang telah ditetapkan, masing-masing. Selain itu, keputusan eksperimen mengesahkan bahawa sistem EHA dengan FLSMCPID mencapai 82.1%, 78.9%, 94.8%, dan 88.8% peningkatan dalam kawalan penjejakan ketepatan untuk 0.25 Hz sinusoidal, berbilang-sinusoidal, titik-ke-titik dan trajektori huru-hara, masing-masing, dan meningkatkan keteguhan sebanyak 33.3% berbanding strategi kawalan FLSMC. Adalah dijangkakan bahawa strategi kawalan FLSMC dan FLSMCPID yang dicadangkan boleh digunakan untuk kawalan penjejakan yang berkesan, tepat dan teguh bagi pelbagai sistem EHA.

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Muhamad Fadli Ghani

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LIST OF ABBREVIATIONS

ABC	–	Artificial Bee Colony
ABRH	–	Adaptive Backstepping Robust H_∞
ACO	–	Ant Colony Optimization
AE	–	Absolute Error
AWPSO	–	Adaptive Weighted Particle Swarm Optimization
BFA	–	Bacterial Foraging Algorithm
CG	–	Cauchy and Gaussian Mutations
CSA	–	Cuckoo Search Algorithm
CW	–	Cauchy Mutation and Mass Weighing
DAQ	–	Data Acquisition System
DE	–	Differential Evolution
DNN	–	Dynamic Neural Networks
EHA	–	Electrohydraulic Actuator
EHFLS	–	Electrohydraulic Force Loading System
EHLS	–	Electrohydraulic Load Simulator
EHSS	–	Electrohydraulic Servo System
ESO	–	Extended State Observer
FI	–	Fuzzy Inference
FL	–	Fuzzy Logic
FLNI	–	Fuzzy Logic Negative Input
FLNO	–	Fuzzy Logic Negative Output

FLPI	–	Fuzzy Logic Positive Input
FLPO	–	Fuzzy Logic Positive Output
FLZI	–	Fuzzy Logic Zero Input
FLZO	–	Fuzzy Logic Zero Output
FLSMC	–	Fuzzy Logic Sliding Mode Control
FLSMCPID	–	Hybrid FLSMC with Proportional-Integral-Derivative Control
FOPID	–	Fractional-Order Proportional-Integral-Derivative
GA	–	Genetic Algorithm
GPC	–	Generalized Predictive Controller
GSA	–	Gravitational Search Algorithm
IAE	–	Integral Absolute Error
ISE	–	Integral Square Error
ITAE	–	Integral Time Absolute Error
LMI	–	Linear Matrix Inequality
LQR	–	Linear Quadratic Regulator
MFS	–	Membership Functions
MPC	–	Modified Predictive Control
MR	–	Magneto-Rheological
MRAC	–	Model Reference Adaptive Control
MSE	–	Mean Square Error
NN	–	Neural Network
NOM	–	Nominal
P	–	Proportional
PI	–	Proportional-Integral
PID	–	Proportional-Integral-Derivative
PSO	–	Particle Swarm Optimization
PSOGSA	–	Particle Swarm Optimization-Gravitational Search Algorithm

RI	–	Robustness Measurement Index
RMPC	–	Robust Model Predictive Controller
RMSE	–	Root Mean Square Error
SISO	–	Single Input and Output
SMC	–	Sliding Mode Control
SSE	–	Sum Square Error
VAR	–	Variation
VSC	–	Variable Structure Control
ZN	–	Ziegler-Nichols

LIST OF SYMBOLS

a_0, a_1, a_2	–	EHA system parameters obtained from the system identification
A_p	–	Cylinder piston surface area
b_i	–	Sinusoidal signal amplitude
c_1, c_2	–	Acceleration constants
C_{tp}	–	Total leakage coefficient of the cylinder piston
e	–	System tracking error
$f(P_L)$	–	Function of internal and external oil leakage non-linear influence
F_a	–	Generated force
f_i	–	Input frequency
$fuzz()$	–	Fuzzy logic function
$gbest_{ij}$	–	Global best position
i	–	Swarm of individuals
J	–	Fitness value
k	–	Constant of reaching law
K_c	–	Flow-pressure coefficient
k_p, k_i, k_d	–	Derivative, Integral, Proportional parameters of PID sliding surface
K_q	–	Flow-gain coefficient
M_t	–	Load mass
n	–	Order for the model of the EHA system
P	–	Supply pressure
p	–	Number of the model parameters

$pbest_{ij}$	–	Personal best position
P_L	–	Pressure drops
Q_L	–	Total oil flow rates
r	–	Reference trajectory
r_1, r_2	–	Random function values
s	–	Sliding surface
$sign()$	–	Signum function
t	–	Time
T	–	Tracking process period
u	–	Input signal
V_{ij}^N	–	Velocity of the Nth particle
V_{ij}^{N+1}	–	New velocity of the Nth particle
V_t	–	Total compressed oil volume
w	–	Inertia weight
$\dot{x}_p$	–	Cylinder piston velocity
X_{ij}^N	–	Position of the Nth particle
X_{ij}^{N+1}	–	New position of the Nth particle
x_p	–	Piston trajectory
β	–	Effective bulk-modulus coefficient
ε	–	Constant of reaching law
λ	–	Control gain coefficient factor of the sliding surface

LIST OF PUBLICATIONS

Journal:

1. Ghani, M.F., Ghazali, R., Jaafar, H.I., Soon, C.C., Sam, Y.M. and Has, Z., 2022. Improved Third Order PID Sliding Mode Controller for Electrohydraulic Actuator Tracking Control. *Journal of Robotics and Control (JRC)*, 3(2), pp.219-226.
2. Ghani, M.F., Ghazali, R., Jaafar, H.I., Soon, C.C., Sam, Y.M. and Has, Z., 2022. Third-Order Robust Fuzzy Sliding Mode Tracking Control of a Double-Acting Electrohydraulic Actuator. *International Journal of Emerging Technology and Advanced Engineering (IJETAE)*, 12(6), pp.141-151.
3. Ghani, M.F., Ghazali, R., Jaafar, H.I., Soon, C.C., Sam, Y.M. and Has, Z., 2022. Fractional Order Integral Sliding Mode Tracking Control of a Third-Order Double-Acting Electrohydraulic Actuator Model. *International Journal of Mechanical Engineering and Robotics Research (IJMERR)*, 11(9), pp.669-675.

Conference Paper:

1. Ghani, M.F., Ghazali, R., Jaafar, H.I., Soon, C.C., Shern, C.M. and Has, Z., 2021, August. The Effects of Mass Variation on Closed-loop EHA System under High Leakage Flow Condition. In *2021 11th IEEE International Conference on Control System, Computing and Engineering (ICCSCE)*, pp. 206-209.
2. Ghani, M.F., Ghazali, R., Jaafar, H.I., Soon, C.C., Jamaluddin, A.Z. and Has, Z., 2022, August. Robust Optimized Sliding Mode Tracking Control of an Electrohydraulic