HARDWARE-IN-THE-LOOP STUDY OF A HYBRID ACTIVE FORCE CONTROL SCHEME OF AN UPPER-LIMB EXOSKELETON FOR PASSIVE STROKE REHABILITATION

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy.

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STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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Thesis submitted in fulfilment of the requirements
for the award of the degree of
Doctor of Philosophy

Faculty of Manufacturing Engineering

UNIVERSITI MALAYSIA PAHANG

AUGUST 2018

ACKNOWLEDGEMENTS

I guess this is one of the hardest past to write, as I doubt that I could acknowledge everyone that has somewhat contributed towards me pursuing this rather dreadful, yet worthwhile path. I am grateful to my parents, for having faith in me and for supporting my pursuit in acquiring the pinnacle of academic achievement. I would also like to thank my sister for telling my parents that I'll be okay over the years.

I would like to thank my PhD supervisor, Prof. Zahari Taha, for being a real pain in the neck over the past four years. Nonetheless, having said that, needless to say, I have learnt and gained more than I should have under his guidance to become a more well-rounded academic and I must say, the experience is priceless. Not forgetting the engaging 'pufte' sessions we had that has resolved a number of issues both PhD and non-PhD related.

My utmost gratitude goes to the late Assoc. Prof. Dr. Rosman Ahmad, the man who was responsible for grooming me to become an academic like him. May God bless his soul. To my teachers, Dr. Hj. Shahrani Hj. Anuar, Ahmad Fakhri Hj. Shaari and Assoc. Prof. Dr. Jamaluddin Mahmud, thank you all for being the best of teachers/lecturers throughout my undergraduate days up till this very day.

I would like to thank the Innovative Manufacturing, Mechatronics and Sports Laboratory members; Azraai 'the Chieftain', Rabiu 'MosaSosas', Amirul 'Yesus', Ismail, Wong 'the Procrastinator', Izzy 'Blackout', Wan Hasbullah, Dr. Hasnun 'the Fuhrer', Jessnor 'the Master Procrastinator', Qastalani, Fay, Abdul Hakim Deboucha, Dr. Aizzat, Dr. Fakhri, Dr. Shah, Yusri, Muaz and Ash (I hope I didn't miss anyone out) for keeping my 'sanity' intact and made my stay at the lab a memorable one.

On a more personal note, I would like to thank my wife, Dr. Sharifah Maszura for being patient, understanding and taking good care of my first born, Saffiya over the course of these past few years. Thank you. As for the apple of my eyes, Saffiya, this thesis is dedicated to you.

ABSTRAK

Beban strok memerlukan pengunaan teknologi robotik untuk mengurangkan ketidakupayaan ahli fisioterapi untuk menampung permintaan yang semakin meningkat untuk pemulihan mangsa strok. Latihan gerakan pasif yang berterusan menunjukkan bahawa pesakit strok boleh mendapatkan semula pergerakan mereka. Tambahan pula, bentuk pemulihan ini adalah penting terutamanya dalam fasa neurorehabilitasi akut dan sub-akut. Tesis ini bertujuan untuk menilai satu kelas skim kawalan yang tegap iaitu kawalan daya aktif (AFC) pada dua darjah kebebasan rangka luar anggota atas yang dapat mengimbangi gangguan yang timbul daripada berat bahagian atas yang berbeza dan unik untuk setiap individu tanpa perlu untuk penalaan semula. Untuk menilai keberkesanan pengawal yang dicadangkan, siasatan simulasi dilakukan. Dinamik sistem yang di nilai itu diperolehi berdasarkan rumus Euler-Lagrange dengan memasukkan pengukuran antropometri pada anggota atas manusia. Keberkesanan pengawal yang dicadangkan, iaitu senibina terbitan berkadaran (PD) AFC (PDAFC) klasik yang dioptimumkan melalui logik kabur (FL), rangkaian neural buatan (ANN), pengoptimuman kawanan partikel (PSO) dan simulasi penapisan Kalman (SKF) terhadap pengendalian PD klasik dalam mengurangkan konfigurasi gangguan yang berbeza (tiada gangguan, gangguan berterusan 30 N.m. dan gangguan harmonik 30 N.m. pada kekerapan 10 Hz pada kelajuan yang berbeza, iaitu perlahan (0.375 rad/s), sederhana (0.430 rad/s) dan pantas (0.502 rad/s) trajektori pemulihan yang lazim untuk sendi bahu dan siku dinilai. Hasil keputusan dari penyiasatan simulasi menunjukkan bahawa skim PDSKFAFC adalah lebih baik berbanding semua skim yang dinilai, terutamanya skim kawalan PD klasik. Satu model berasaskan data dibangunkan berdasarkan prototaip rangka luar anggota atas manusia yang dibina. Satu simulasi perkakasan-dalam-gelung dijalankan untuk menilai gandaan yang bersesuaian bagi parameter PD dan inersia AFC yang diperolehi melalui algoritma SKF. Hasil keputusan eksperimen menunjukkan bahawa skim PDSKFAFC mampu mengimbangi gangguan yang disebabkan oleh jisim lengan atas (2 kg) dan lengan bawah boneka (1.5 kg) masing-masing kepada prototaip rangka luar berbanding dengan skim PD klasik.

ABSTRACT

The burden of stroke has necessitated the employment of robotics to mitigate the inability of physiotherapists to cope with the increasing demand for rehabilitation by stroke survivors. Continuous passive motion training has been demonstrated to be able to allow stroke patients to regain their mobility. Furthermore, this form of rehabilitation is non-trivial particularly in the acute and sub-acute phase of neurorehabilitation. This thesis aims at evaluating a class of robust control scheme, namely active force control (AFC) on a two degrees of freedom upper-limb exoskeleton that is able to compensate disturbances arising from different upper-limb weights that are unique for different individuals without the need for further re-tuning. In order to evaluate the efficacy of the proposed controller, a simulation investigation was performed. The dynamics of the system are derived based on the Euler-Lagrange formulation by incorporating anthropometric measurements of the human upper limb. The efficacy of the proposed controllers, namely classical Proportional-Derivative AFC (PDAFC) architecture optimised by means of fuzzy logic (FL), artificial neural network (ANN), particle swarm optimisation (PSO) and simulated Kalman filter (SKF) against classical PD control in mitigating different disturbance configurations (no disturbance, constant disturbance of 30 N.m. and harmonic disturbance of 30 N.m. at a frequency of 10 Hz at different speeds, i.e., slow (0.375 rad/s), medium (0.430 rad/s) and fast (0.502 rad/s) of a typical rehabilitation trajectory for the shoulder and elbow joints were evaluated. It is shown from the simulation investigation that the PDSKFAFC scheme is better in comparison to all the evaluated schemes, particularly the classical PD control scheme. A data-driven model is developed based on the exoskeleton prototype built. A hardware-in-the-loop simulation is carried out to evaluate the appropriate gains of both the PD and the AFC inertial parameter gained that is tuned via the SKF algorithm. It is demonstrated through the experimental works, that the PDSKFAFC scheme is able to compensate against the disturbance attributed by the attached mannequin mass of the upper arm (2 kg) and forearm (1.5 kg), respectively to the exoskeleton prototype in comparison the classical PD scheme.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

IN	Estimated Mass/ Estimated Inertial Matrix
θ_1	Shoulder joint angle
θ_2	Elbow joint angle
L	Lagrangian
K	Kinetic energy
P	Potential energy
τ_d	Disturbance torque
g	Gravity
J	Mass moment of inertia
m	Mass
e	Angular position error
$\dot{e}$	The rate of angular position error
K_d	Derivative gain
K_p	Proportional gain
$\ddot{\theta}$	Measured acceleration signal
τ	Measured actuation torque
x	Constant
b	Bias
R	Correlation coefficient
R^2	Coefficient of determination
s_i^{k+1}	Next particle position
s_i^k	Current particle position
v_i^{k+1}	Velocity of particle
r_1	Random number
r_2	Random number
c_1	Cognitive learning factor
c_2	Social learning factor
pbest	Personal best
gbest	Global best
ω	Inertia weight

k	*k*-th generation
n	Swarm size
P	Error covariance estimate
Q	Process noise
R	Measurement Noise
$\mathbf{Z}_i(t)$	Measurement of each individual agent
$K(t)$	Kalman gain
t	Iteration
I	Current
K_t	Torque constant
IN*	Modified IN

LIST OF ABBREVIATIONS

AFC	Active Force Control
ANN	Artificial Neural Network
CEACS	Combined Energy and Attitude Control System
CTC	Computed Torque Control
FL	Fuzzy Logic
HIL	Hardware-in-the-Loop
MAE	Maximum of the Absolute Error
MSE	Mean Squared Error
MSD	Means and Standard Deviations
mSMERL	Modified Sliding Mode Exponential Reaching Law
PC	Personal Computer
PID	Proportional-Integral-Derivative
PD	Proportional-Derivative
PI	Proportional-Integral
PSO	Particle Swarm Optimisation
RAC	Resolved Acceleration Control
RMSE	Root Mean Squared Error
SKF	Simulated Kalman Filter
SMC	Sliding Mode Control
WAM	Whole Arm Manipulator

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