MODEL PREDICTIVE CONTROL WITH ANGULAR ACCELERATION CONSTRAINT OF PROPORTIONAL SERVO-HYDRAULIC LOWER EXTREMITY ROBOTIC DEVICE

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ABSTRACT

Lower Extremity Robotic Device (LERD) is a four-degree of freedom hydraulic exoskeleton that assists the paralysed patient to walk. The nonlinear dynamic model of the hydraulic exoskeleton system used in Model Predictive Control (MPC) is challenging to be modelled, especially in the state-space model form. Traditional torque constraint technique restricts the exoskeleton to provide wide variability of wearers' weight. For a heavy wearer, the torque constraint could limit the system's performance where the hydraulic force will be cut off when exceeds the predetermined torque. Angular acceleration constraint could be an alternative method to overcome the weight variations among different wearers. However, this technique has not been reported elsewhere in the literature. This study aimed to develop mathematical models of the empiric relationship between the median of absolute angular accelerations and pulse width modulation duty cycle of the LERD exoskeleton to facilitate system interfacing. An optimal motion constrained MPC controller for trajectory tracking was designed first, and the results were benchmarked with Proportional-Integral-Derivative (PID) controller. Using cross-correlation analysis, the dynamic models were then selected and used to analyse the designed controllers. The average absolute trajectory tracking error (AATTE) was chosen as the performance parameter with the AATTE closer to zero-degree reference point indicates better trajectory tracking. Results of the simulation study for both MPC and PID controllers at three different speeds showed that AATTE became farther as the walking speed increased. Benchmarked for simulation result showed that the PID controller produced closer AATTE of all joints compared to the MPC controller at the slowest speed (0.3m/s). However, as the speed increased, the MPC controller achieved closer AATTE of all joints than the PID controller. The simulation results were further validated with an experimental study at 0.3m/s. After cross-correlation analysis between reference and output trajectories, the PID controller has produced all joints' AATTE of 2.64 degrees nearer to zero degrees than the MPC controller's AATTE of all joints (2.99 degrees). In overall, the MPC controller exhibits a smoother control signal compared to the PID controller where the latter produces fluid hammer during operation which can harm the wearer and potential to cause possible damage to the exoskeleton system's components. The proposed control system is able to avoid the need to derive several important parameters such as valve's orifice area, flow coefficient, frictions, etc. Based on the findings of this study, it can be concluded that the proposed simulation and prototype models together MPC controller are acceptable for use in the exoskeleton control system.

ABSTRAK

Peranti Robot Lampauan Bawah (LERD) adalah sebuah eksorangka hidraulik empat darjah kebebasan yang membantu pesakit lumpuh untuk berjalan. Model dinamik tak lelurus sistem eksorangka hidraulik yang digunakan dalam Kawalan Ramalan Model (MPC) sukar untuk dimodelkan, terutama dalam bentuk model keadaan-ruang. Teknik kekangan kilas tradisional menghadkan eksorangka untuk menampung pelbagai berat para pemakai. Bagi pemakai yang berat, kekangan kilas boleh menghadkan prestasi sistem yang mana daya hidraulik akan terpotong apabila melebihi kekangan kilas yang telah ditentukan. Kekangan pecutan sudut boleh menjadi kaedah alternatif untuk mengatasi variasi berat antara para pemakai yang berbeza. Walau bagaimanapun, teknik ini tidak dilaporkan di mana-mana dalam literatur. Kajian ini bertujuan untuk membangunkan pemodelan matematik hubungan empirik antara median pecutan sudut mutlak dan kitar tugas pemodulatan lebar denyut eksorangka LERD untuk memudahkan pengantaramukaan sistem. Pergerakan optimum terkekang pengawal MPC untuk penjejakan trajektori direkabentuk dahulu, dan keputusan telah ditanda aras dengan pengawal Perkadaran-Kamiran-Terbitan (PID). Dengan menggunakan analisis sekaitan-silang, model dinamik kemudiannya dipilih dan digunakan untuk menganalisis pengawal yang telah direkabentuk. Ralat penjejakan trajektori mutlak purata (AATTE) telah dipilih sebagai parameter prestasi dengan AATTE lebih dekat kepada titik rujukan darjah-sifar yang menunjukkan penjejakan trajektori yang lebih baik. Keputusan kajian penyelakuan untuk kedua-dua pengawal MPC dan PID pada tiga kelajuan yang berbeza menunjukkan bahawa AATTE menjadi semakin jauh ketika kelajuan berjalan semakin meningkat. Keputusan penanda aras untuk keputusan penyelakuan menunjukkan bahawa pengawal PID menghasilkan AATTE semua sendi yang lebih dekat berbanding dengan pengawal MPC pada kelajuan yang paling perlahan (0.3m/s). Walau bagaimanapun, semakin kelajuan meningkat, pengawal MPC mencapai AATTE semua sendi yang lebih dekat berbanding dengan pengawal PID. Keputusan penyelakuan selanjutnya disahkan dengan kajian ujikaji pada 0.3m/s. Selepas analisis sekaitan-silang antara trajektori rujukan dan keluaran, pengawal PID telah menghasilkan AATTE semua sendi iaitu 2.64 darjah lebih hampir kepada darjah sifar berbanding dengan AATTE pengawal MPC semua sendi (2.99 darjah). Secara keseluruhan, pengawal MPC didapati mempamerkan isyarat kawalan yang lebih licin berbanding dengan pengawal PID yang mana, yang terkemudian menghasilkan tukul bendalir semasa operasi yang boleh membahayakan pemakai dan berpotensi menghasilkan kerosakan kepada komponen sistem eksorangka. Sistem kawalan yang dicadangkan boleh mengelakkan keperluan untuk menerbitkan beberapa parameter penting seperti luas orifis injap, pekali aliran, geseran dan lain-lain. Berdasarkan penemuan kajian ini, dapat disimpulkan bahawa model penyelakuan dan prototaip bersama pengawal MPC dapat diterima untuk digunakan dalam sistem kawalan eksorangka.

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LIST OF ABBREVIATIONS

a/a	-	Abduction/Adduction
AATTE	-	Average Absolute Trajectory Tracking Error
APAL	-	Active Power-Assist Lower Limb
BLEEX	-	Berkeley Lower Extremity Exoskeleton
CAEP	-	China Academy of Engineering Physics
CASWELL		CAEP-SWUJTU Lower Load Exoskeleton
d/p	-	Dorsi/Plantar Flexion
DARPA	-	Defense Advanced Research Projects Agency
DC	-	Direct Current
DOF	-	Degree of Freedom
ECUST	-	East China University of Science and Technology
EHPA	-	Exoskeletons for Human Performance Augmentation
ELEBOT	-	ECUST Leg Exoskeleton roBOT
eLEGS	-	Exoskeleton Lower Extremity Gait System
EMG	-	Electromyography
f/e	-	Flexion/Extension
FES	-	Functional Electrical Stimulation
FLA	-	Fuzzy Logic Algorithm
FUM	-	Ferdowsi University of Mashhad
HTE	-	Human Torque Estimation
HUALEX	-	HUman-powered Augmentation Lower EXoskeleton
HyPER	-	Hydraulically Powered Exoskeletal Robot
i/e	-	Internal/External
inv/ev	-	Inversion/Eversion
LERD	-	Lower Extremity Robotic Device
LOPES	-	LOwer extremity Powered ExoSkeleton
MPC	-	Model Predictive Control
MOSFET	-	Metal-Oxide Semiconductor Field-Effect Transistor
N/A	-	Not Available
NAEIES	-	Naval Aeronautical Engineering Institute Exoskeleton

NI - National Instruments

NMPC - Nonlinear Model Predictive Control

P - Proportional

PD - Proportional-Derivative

PFCVM - Proportional Flow Control Valve Manifold

PI - Proportional-Integral

PID - Proportional-Integral-Derivative

PMA - Pneumatic Muscle Actuator

PWM - Pulse Width Modulation

ROM - Range of Motion

rSEA - Rotary Series Elastic Actuator

SCI - Spinal Cord Injury

SDATTE - Standard Deviation of Absolute Trajectory Tracking Error

SEA - Series Elastic Actuator

SWJTU - Southwest Jiatong University

LIST OF SYMBOLS

N_P - Prediction horizon

N_C - Control horizon

t - Current sampling interval

i,j,k - Index

$t + j$ - Future sampling interval

$\hat{y}(t + j|t)$ - Future output

$y(t)$ - Current output

$u(t + j|t)$ - Future control signal

$y_r(t + j)$ - Reference trajectory

$u(t|t)$ - Current control signal

$S_y(t)$ - Weighted sum of squared deviations

$S_{\Delta u}(t)$ - Weight sum of controller adjustments

$S_u(t)$ - Weighted sum of manipulated variable deviations

n_y - Number of plant output

n_u - Number of manipulated variables

y_{ri} - Setpoint (reference trajectory) of ith variable

y_i - Output of ith control variable

$\overline{u}_i$ - Nominal value of ith input

w_{yi} - ith output weight

$w_{\Delta ui}$ - ith rate weight

w_{ui} - ith input weight

Δu_i - Predicted change in ith manipulated variable

V - Voltage

θ - Angular position (Joint angle)

θ_d - Angular position desired (reference) input

$\omega, \dot{\theta}$ - Angular velocity

$\alpha, \ddot{\theta}$ - Angular acceleration

$u,\ddot{\theta}_c$ - Angular acceleration control signal

DC,DC_i - Pulse width modulation (PWM) duty cycle

$\ddot{\theta}_m$ - Median of absolute angular acceleration

DC_0 - PWM duty cycle threshold

e_t - Error threshold

I - Current

Q - Flow rate

$\hat{I}$ - Signed current

v_r,v_e,$\dot{c}$ - Linear velocity of hydraulic cylinder stroke

τ - Torque

d_1,d_2 - Piston diameter and piston rod diameter

A_r,A_e - Areas of hydraulic cylinder retraction and extension

a,b,r - Length

c - Length of hydraulic cylinder extension

θ_H - Angle of hip joint with respect to vertical axis

θ_K - Angle of knee joint with respect to hip joint angle, θ_H

θ_{1c},θ_{2c},γ - Angle

L_s - Stroke length

(x_b, y_b) - Base coordinate

L_i - Length of link i

L_{ic} - Distance between the center of mass and the upper joint of link i

θ_i - Angle of link i

m_i - Mass of link i

I_i - Moment of inertia for link i

(x_{ic}, y_{ic}) - Coordinate for the center mass of link i

$\dot{x}_{ic}$,$\dot{y}_{ic}$ - Linear velocity of center mass for x and y axes of link i

$\dot{x}_b$,$\dot{y}_b$ - Linear velocity for x and y axes at base point

L - Langrangian

n - Number of degree of freedom (DOF)

K - Kinetic energy

P - Potential energy

T,T_θ - Force and torque matrix

D - Inertia matrix

H - Centrifugal and Coriolis torque matrix

G	-	Gravitational torque matrix
K_P,K_I,K_D		Parameters of Proportional-Integral-Derivative (PID) controller
X	-	Time delay
Y	-	Cross-correlation coefficient

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CHAPTER 1

INTRODUCTION

1.1 Problem Background

During the early stages of robotic systems development, most of their systems were hydraulically powered. However, hydraulic actuation has lost favour in various fields of mechatronics in the last decades since the electrical actuation (e.g., brushed and brushless DC motors) took over due to size, weight, price, ease, and accuracy of control (Yang *et al.*, 2009; Cunha *et al.*, 2010). The hydraulic system needs a complex control algorithm in order to handle its flow dynamics and motor friction. They also require an expensive installation, including a pump, reservoir, manifolds, valves, and hoses (Otten *et al.*, 2015). Furthermore, hydraulic oil can leak out easily causes environmental pollution (Li *et al.*, 2015). Still, the requirements for dealing with heavy objects and fast response to external disturbances and inputs have lately exhibited a renewed interest in hydraulic actuators and their application in the robotics field. Compared to electrical actuation, hydraulic actuation systems have high power-to-weight ratio, a wide range of speed operating conditions, swift dynamic response, overload protection, and reliability in outdoor environments. By considering these advantages, hydraulic actuation fulfils all the requirements that show a good and effective driving method for legged robots (Semini *et al.*, 2011).

The hydraulic actuators have been mainly considered within the robotics community for several years not to fit the dynamic control challenges in locomotion robots since these actuators are difficult to control (Cunha *et al.*, 2010). However, the usage of the hydraulic actuator in the robotics field has recently increased with some successful applications such as Kenken (Hyon and Mita, 2002), COMET-III (Nonami *et al.*, 2003; Barai and Nonami, 2008), BigDog (Buehler *et al.*, 2005; Raibert *et al.*, 2008), HyQ (Semini, 2010), and SARCOS (Hyon *et al.*, 2007). As for the hydraulically actuated exoskeletons, only a few of them have been reported, and most of them are designed as the power augmentation exoskeletons (e.g., BLEEX, UESuit, and HyPER) that concentrate on the power amplifier to enhance the wearer’s stamina and strength when carrying heavy objects (Yang *et al.*, 2008). The hydraulic actuator is rarely chosen to develop the lower limb assistive and rehabilitation exoskeletons that focus more on assisting the paralysed patients to walk and recover their mobility.

1.2 Problem Statement

The hydraulic exoskeletons can help the wearer to carry heavy loads and handle large force tasks because the hydraulic actuator has high power-to-weight ratio, large bandwidth, and fast dynamic response (Mavroidis *et al.*, 1999; Cunha *et al.*, 2010; Khan *et al.*, 2015; Mattila *et al.*, 2017). These advantages are particularly important for rehabilitating the paralysed patients and handling heavy loads in the military, shipbuilding, construction, industries, etc. Despite these favourable features, the hydraulic actuator is challenging to control, owing to its nonlinear characteristics. Therefore, this study proposes a novel Model Predictive Control (MPC) control strategy for the accurate actuation of hydraulic cylinders in the exoskeleton system. The MPC controller’s main advantage is it optimizes the current time interval while keeping future time intervals in the account. Besides, the MPC controller can predict future events and take control actions appropriately, while the conventional PID controller does not have this predictive ability. The MPC controller can also handle constraints that the PID controller is not capable of it.

The MPC controller’s system model is required in the MPC control architecture design of the nonlinear hydraulic actuated exoskeleton system. However, this nonlinear dynamic model is challenging to be modelled, especially in the state-space model form. The hydraulic exoskeleton has high nonlinear dynamics and parameter uncertainties of the Lagrange’s dynamic equation, hydraulic cylinder’s friction force, hydraulic fluid compressibility, and valve’s flow rate-pressure characteristics (Sheng and Li, 2016). Thus, an alternative state-space model form of the hydraulic exoskeleton system can be designed using angular acceleration inputs and angular position outputs. These motion constraints are derived based on average healthy human walking gait data. Angular acceleration constraint is applied instead of torque constraint to avoid the torque restriction if the exoskeleton is required to displace a heavier subject. For a heavy subject, the torque constraint could limit the system’s performance where the hydraulic force will be cut off when exceeding the predetermined torque. However, this method has not been reported elsewhere in the literature.

Real-life implementation of MPC controller in exoskeleton motion control also poses a big hindrance to the practical issue of MPC controller. The solution of the nonlinear hydraulic actuation system model could be more demanding on the computational resources. One such application is converting MPC control signals to appropriate current and voltage signals, which could be challenging to model and numerically solve. The MPC control signal is usually represented in the form of torque. However, the relationship between the computed control torque and its corresponding electro-hydraulic input signal is highly nonlinear and difficult to be modeled. It is well-known that a rotational torque is proportional to exoskeleton inertia, which is nonlinear and dependent on system dimension and current states. Translational acceleration is a more appropriate choice in the search for converting the MPC control signal to the hydraulic cylinder because both of them move on the same axis. Therefore, this study hypothesizes that angular acceleration is used instead of torque. Also, an empirical approach is resorted for establishing the relationship between the MPC control signal and the electro-hydraulic signal.

The hydraulic actuator’s ability can harm the wearer of the hydraulic exoskeleton system if it exceeds his range of motion (ROM) and strength. Therefore, safety is an important issue in this exoskeleton system since the wearer is strapped into it (B. Chen *et al.*, 2016; Huo *et al.*, 2016). The risks can be reduced by implementing passive and active safety mechanisms into the exoskeleton system (Tucker *et al.*, 2015). The passive safety mechanisms restrict the exoskeleton’s power transmission without needing any input power or feedback control. One of these mechanisms is the physical stoppers placed at the exoskeleton mechanical structure to constrain the ROM and resist the maximum intrinsic force/torque that the actuators can generate (Zoss *et al.*, 2006; Bortole *et al.*, 2015; B. Chen *et al.*, 2016). Besides that, the electrical circuits are constructed with suitable fuses and grounding to enhance safety. The external emergency switches deactivate the powered exoskeleton manually to protect the wearer from unexpected accidents while walking (Chen *et al.*, 2007; Long *et al.*, 2017). The active safety mechanisms restrict the exoskeleton's power transmission using the feedback control that usually needs input power (Tucker *et al.*, 2015). These mechanisms consist of configuration-dependent actuation torque and ROM constraints in the control system. The redundant sensors can monitor the system's performances (e.g., velocity and human-exoskeleton interaction force) in real-time and detect the actuator, sensor, or controller failures. If there is a system failure, the exoskeleton system should warn the wearer about resetting or recovering the controller system. The exoskeleton should also be designed with an emergency shutdown system to prevent the wearer from being injured.

The controller design is a critical part of the exoskeleton system development, where it has important aspects such as the level of patient participation, overall safety, and robotic transparency (Pennycott *et al.*, 2012). The exoskeleton control system is designed according to the principle that this robotic device can mimic the human's movement intention, but it does not obstruct the human movement (Low, 2011). For example, a simple position-controlled system tracks the joint reference trajectories, but it minimizes the system's adaptability. Thus, different sensors are required to obtain the system and environment information for implementing higher-level control. One of the important aspects of the control system is the wearer's safety. Since the current exoskeleton robots are programmed under complex algorithms, it is hard to secure their safety by controlling their physical stability such as damaged parts. A dangerous accident can happen if a small bug in the control programming software (Hasebe *et al.*, 2014). Thus, safety measures have been made to guarantee the software safety of exoskeleton robots. Furthermore, safety should be integrated into the exoskeleton control system to warrant the user's safety and stability in emergency conditions (B. Chen *et al.*, 2016). The system incorporates the safety layers to achieve safe human-exoskeleton interaction, particularly considering the amount of power these robotic devices can produce (Tucker *et al.*, 2015).

Algorithmic restrictive motion constraints could be presented in many forms, like restraining the actuator motion range, speed, acceleration, and lifting strength, in accordance with the most stringent human safety requirements. The strategies are to design the controller that avoids forcing the limb into inappropriate configurations or motions that could physically harm the patient’s limbs. It is well known that Model Predictive Controller (MPC) has the ability to apply constraints, which makes it suitable for the synthesis of optimal safety walking patterns and motion control (Kajita and Espiau, 2008).

1.3 Research Objectives

The research work detailed in this thesis aims to contribute in a very small degree to the existing sphere of knowledge in hydraulic exoskeleton control design. In order to achieve the aim of this research, the objectives are outlined as follows:

(a) To develop mathematical models of the empiric relationship between the angular acceleration and input electro-hydraulic control signal of the Lower Extremity Robotic Device (LERD) exoskeleton to facilitate system interfacing.

(b) To develop simulation and prototype models of the LERD control system for simulation and experimental studies respectively, with angular acceleration as the controller output.

(c) To design Model Predictive Control (MPC) for position control of the four-degree of freedom (DOF) LERD exoskeleton with constrained angular acceleration and angular position.

1.4 Scopes of Research

Several scopes were explored to achieve the research objectives. The scopes of this research are:

(a) Mathematical modelling for kinematics and dynamics of a five-link human bipedal model wearing a four-DOF LERD exoskeleton in the sagittal plane.

(b) Discrete-time state-space formulation of the MPC controller’s internal system model through the computational platform by MATLAB Simulink 2017b.

(c) Empirical translation of the MPC controller’s control signal (angular acceleration) into the PWM duty cycle’s electrical signal.

(d) The trajectory tracking performance of the MPC controller in the LERD exoskeleton is assessed through simulation and experimental studies.

(e) Validation of the MPC controller with the Proportional-Integral-Derivative (PID) controller.

1.5 Research Contributions

One of the contributions in this study is the mathematical modelling of empiric relationships between the angular acceleration (controller output) and pulse width modulation (PWM) duty cycle signals at the hip and knee joints of the LERD exoskeleton. Data collection during retraction and extension movements are carried out from the LERD exoskeleton to achieve the joint’s median of absolute angular acceleration value based on the PWM duty cycle value. The empirical relationships of hip and knee joints are then inserted into the LERD control system architecture for converting its angular acceleration control signal outputs to the PWM duty cycle. These empirical relationships also can describe the characteristics of hip and knee joints during retraction and extension movements directly from the real hydraulic exoskeleton system. The hydraulic cylinder at the knee joint needs to lift and hold the lower leg (between knee and ankle), lighter than the whole leg (between hip and ankle) lifted and held by the hip joint. Therefore, the hydraulic cylinders' characteristics at these joints are different because of their different positions.

The second contribution is the development of simulation and prototype models of the LERD control system for simulation and experimental studies respectively, with angular acceleration as controller output. Unlike the conventional modelling method, the proposed models use angular acceleration as the controller's output because it is easy to measure and proportionally related to torque. Besides, constraining the angular acceleration does not limit the hydraulic cylinder's output torque/force, especially when people with different weights and strengths use the exoskeleton. It is different from the controller's torque, force, or pressure constraints, where the hydraulic force will be cut off when exceeding the predetermined torque limit if a heavy subject uses the exoskeleton. Therefore, the simulation and prototype models are designed using an alternative method without considering the crucial component parameters such as valve's orifice area, flow coefficient, discharge coefficient, fluid density, frictions, etc. These models employ the mathematical model of empiric relationships between the median of absolute angular acceleration and PWM duty cycle directly obtained from the LERD exoskeleton system. The PWM duty cycle values are calculated based on the median of absolute angular acceleration values to regulate the proportional flow control valve in the LERD exoskeleton system. Besides, the simulation model also uses the PWM duty cycle-current and current-flow rate converters based on the proportional flow control valve datasheet.

The third contribution is the design and development of an interfacing approach for the MPC controller with angular acceleration control output in the LERD exoskeleton. In this research, the internal MPC controller's system model of the LERD exoskeleton system is defined by linearization based on an alternative discrete-time state-space model form using angular acceleration inputs and angular position outputs. The MPC controller can generate a smooth control signal of angular acceleration to regulate every LERD exoskeleton's joint. Besides, the imposition of the angular position and angular acceleration constraints into the MPC controller warrants the wearer's safety. Therefore, the LERD exoskeleton gives another protection for the wearer besides the mechanical mechanisms in every joint.

1.6 Organization of Thesis

This thesis is organized into five chapters that explain the theoretical aspects and the development process of this research. These chapters are arranged as follows:

Chapter 2 (Literature Review) studies the related topics that can be used in this research, such as previous studies about developing robot-assistive systems and Model Predictive Control (MPC).

Chapter 3 (Research Methodology) describes the theoretical frameworks and methods utilized in the simulation and experimental studies of this research.

Chapter 4 (Results and Analysis) presents the findings and observations in this research. The performance results of the LERD exoskeleton under control of MPC and Proportional-Integral-Derivative (PID) controllers are presented, analysed, and discussed.

Chapter 5 (Conclusion and Recommendations) presents the overall conclusions from this research's results and discusses possible future improvements and recommendations on the LERD exoskeleton system as the contribution for others to acquire from this research.

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1. **Onn, N.**, Hussein, M., Tang, C. H. H., Zain, M. Z. M., Mohamad, M. and Lai, W. Y. (2015) 'Motion Control of Human Bipedal Model in Sagittal Plane', *WSEAS Transactions on Systems and Control*, 10, pp. 160-171. **(Indexed by SCOPUS)**

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