Faculty of Electrical Engineering

POSITIONING CONTROL OF PNEUMATIC ARTIFICIAL MUSCLE SYSTEMS USING IMPROVED NOMINAL CHARACTERISTIC TRAJECTORY FOLLOWING CONTROL

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POSITIONING CONTROL OF PNEUMATIC ARTIFICIAL MUSCLE SYSTEMS USING IMPROVED NOMINAL CHARACTERISTIC TRAJECTORY FOLLOWING CONTROL

TANG TENG FONG

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DECLARATION

I declare that this thesis entitled “Positioning Control of Pneumatic Artificial Muscle Systems using Improved Nominal Characteristic Trajectory Following Control” 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 candidature of any other degree.

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Name : Tang Teng Fong

Date : ………………………………………..

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 Name : Associate Prof. Dr. Chong Shin Horng

Date : …………………………………………….......

DEDICATION

To my beloved parents, Tang Chin Siang and Ong Geok Ee,

For taking good care and giving guidance in life and academic.

To my concerned sister, Tang Hoay Sean,

For giving moral support.

And for those I love very much too.

ABSTRACT

Pneumatic Artificial Muscle (PAM) is a new type of pneumatic actuator that duplicates the behaviour of skeletal muscle, where it contracts to generate a pulling force via pressurised air and retracts passively when air is depressurised. The PAM has the characteristics that meet the need of robotic applications, such as lightweight, high power-to-weight ratio performance, and safe in use characteristic. However, the PAM exhibits strong nonlinear characteristics which are difficult to be modelled precisely, and these characteristics have led to low controllability and difficult to achieve high precision control performance. This research aims to propose and clarify a practical controller design method for motion control of a pneumatic muscle actuated system. A nominal characteristic trajectory following (NCTF) control is proposed, and this controller emphasises simple design procedure, which it is designed without the exact model parameters, and yet is able to demonstrate high performance in both point-to-point and continuous motions. The NCTF control is composed of a nominal characteristic trajectory (NCT) and a PI compensator. The NCT is the reference motion trajectory of the control system, and the PI compensator makes the mechanism motion follows the constructed NCT. The NCT is constructed on a phase plane using the deceleration motion of the mechanism in open-loop positioning condition. However, the conventional NCTF control does not offer a promising positioning performance with the PAM mechanism, where it exhibits large vibration in the steady-state before the mechanism stopping and tends to reduce the motion accuracy. Therefore, the main goal of this study is to improve the conventional NCTF control for high positioning control of the PAM mechanism. The conventional NCTF control is enhanced by removing the actual velocity feedback to eliminate the vibration problem, added an acceleration feedback compensator to the plant model and a reference rate feedforward to solve the low damping characteristic of the PAM mechanism in order to improve the tracking following characteristic. The design procedure of the improved NCTF control remains easy and straightforward. The effectiveness of the proposed controller is verified experimentally and compared with the conventional NCTF and classical PI controls in positioning and tracking motion performances. The experimental results proved that the improved NCTF control reduced the positioning error up to 90% and 63% as benchmarked to the PI and conventional NCTF controls respectively, while it reduced up to 92% (PI) and 95% (NCTF) in the tracking error. In the robustness evaluation, the comparative experimental results demonstrated that the improved NCTF control has higher robust against the irregular signals than the PI and the conventional NCTF controls. This can be concluded that, the improved NCTF control has demonstrated high positioning accuracy and fast tracking performance at different working range and frequencies as well as high robustness against the irregular signals. Overall, the improved NCTF control has showed the capability in performing high precision motion and offered promising results for the PAM mechanism.

ABSTRAK

Penggerak otot tiruan pneumatik (PAM) ialah penggerak baru yang menduplikasi kelakuan otot rangka, ia mengecut untuk menjana kuasa tarikan melalui udara bertekanan dan menarik balik secara pasif apabila dinyahtekanan. PAM mempunyai ciri-ciri yang memenuhi keperluan aplikasi robotik, seperti ringan, prestasi tinggi untuk nisbah kuasa kepada berat, dan selamat digunakan. Sebaliknya, PAM mempamerkan ciri-ciri tidak linear yang ketara menyebabkan ia sukar dimodelkan dengan tepat, dan ciri-ciri tersebut telah membawa kepada kebolehkawalan rendah dan sukar untuk mencapai prestasi kawalan kejituan tinggi. Kajian ini bertujuan untuk mencadangkan dan menjelaskan kaedah reka bentuk pengawal praktikal untuk mengawal pergerakan meja didorong oleh otot-otot tiruan pneumatik. Pengawal mengikut trajektori ciri nominal (NCTF) dicadangkan, dan pengawal ini menekankan prosedur reka bentuk mudah, iaitu ia direka tanpa parameter model yang tepat tetapi dapat menunjukkan prestasi tinggi dalam gerakan titik ke titik dan gerakan berterusan. Pengawal NCTF terdiri daripada trajektori nominal (NCT) dan pemampas PI. NCT ialah gerakan rujukan trajektori sistem kawalan dan pemampas PI membuat gerakan mekanisme mengikut NCT yang dibina. NCT dibina pada satah fasa dengan menggunakan gerakan nyahpecutan mekanisme dalam keadaaan kedudukan gelung buka. Bagaimanapun, pengawal konvensional NCTF tidak menawarkan prestasi kedudukan terjamin bagi mekanisme PAM, di mana ia mempamerkan getaran besar dalam keadaan mantap sebelum mekanisme henti dan cenderung dalam mengurangkan ketepatan gerakan. Oleh itu, matlamat utama kajian ini adalah mempertingkatkan pengawal konvensional NCTF untuk kawalan berketepatan tinggi bagi sistem dorongan otot pneumatik. Pengawal konvensional NCTF dipertingkatkan dengan mengeluarkan maklum balas halaju sebenar untuk menghapuskan masalah getaran, menambah pemampas maklum balas pecutan pada sistem model dan menambah suapan maklum awal kadar rujukan untuk menyelesaikan redaman rendah daripada mekanisme PAM supaya mempertingkatkan sifat penjejakan. Prosedur reka bentuk pengawal tambahbaik NCTF kekal mudah dan langsung. Keberkesanan pengawal yang dicadangkan itu disahkan secara eksperimen dan dibandingkan dengan pengawal konvensional NCTF dan pengawal klasik PI dalam prestasi-prestasi gerakan kedudukan dan gerakan penjejakan. Keputusan eksperimen membuktikan bahawa pengawal tambahbaik NCTF mengurangkan ralat kedudukan sehingga 90% dan 63% berbanding dengan pengawal PI dan pengawal konvensional NCTF, manakala ia mengurangkan sehingga 92% (PI) dan 95% (NCTF) dalam ralat penjejakan. Dalam penilaian keteguhan, keputusan perbandingan eksperimen menunjukkan bahawa pengawal tambahbaik NCTF mempunyai keteguhan lebih tinggi terhadap isyarat tidak teratur berbanding pengawal-pengawal PI dan konvensional NCTF. Ini dapat disimpulkan, pengawal tambahbaik NCTF menunjukkan berketepatan tinggi dan prestasi penjejakan pantas pada jarak kerja dan kekerapan berlainan serta keteguhan tinggi terhadap isyarat tidak teratur. Secara keseluruhan,

pengawal tambahbaik NCTF menunjukkan keupayaan dalam melaksanakan gerakan kejituan tinggi dan keputusan yang memberangsangkan bagi mekanisme PAM.

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LIST OF SYMBOLS AND ABBREVIATIONS

ξ	-	Damping ratio
^{o}	-	Degree
^{o}C	-	Degree Celsius
ψ_1	-	Flow function of PAM1
ψ_2	-	Flow function of PAM2
β	-	Inclination at the origin of the NCT
ψ_{max}	-	Maximum of flow function
ξ_p	-	Practical stability limit
γ	-	Specific heat ratio
τ	-	Time constant
A	-	Effective orifice area
AC	-	Alternating current
AR-CM NCTF	-	Acceleration reference-continuous motion nominal characteristic trajectory following
B	-	Damping coefficient
CM NCTF	-	Continuous motion nominal characteristic trajectory following
DoF	-	Degree-of-freedom
e	-	Error
$\dot{e}$	-	Error rate
E_{max}	-	Peak error

E_{RMS}	-	Root mean square error
E_{ss}	-	Steady-state error
F_1	-	Force of PAM1
F_2	-	Force of PAM2
$F_{friction}$	-	Friction force
FEA	-	Finite element analysis
FLC	-	Fuzzy logic control
G_{ψ}	-	Flow dynamics
G_F	-	Force dynamics
$G_{\dot{m}}$	-	Mass flow dynamics
$G_{\dot{p}}$	-	Pressure dynamics
G_V	-	Volume dynamics
G_x	-	Motion equation
Hz	-	Hertz
J	-	Joule
k	-	System gain
K_a	-	Acceleration feedback compensator
K_p	-	Proportional gain
K_{pu}	-	Ultimate proportional gain
K_i	-	Integral gain
K	-	Kelvin
kg	-	Kilogram
kHz	-	Kilohertz
kPa	-	Kilopascal

$\dot{m}_1$	-	Mass flow rate of PAM1
$\dot{m}_2$	-	Mass flow rate of PAM2
M	-	Mass of the mover
m	-	Metre
MIMO	-	Multiple-input and multiple-output
MISO	-	Multiple-input and single-output
mm	-	Millimetre
MPa	-	Megapascal
ms	-	Millisecond
N	-	Newton
NCT	-	Nominal characteristic trajectory
NCTF	-	Nominal characteristic trajectory following
nm	-	Nanometre
NN	-	Neural network
OS	-	Overshoot
P_1	-	Pressure of gas of PAM1
P_2	-	Pressure of gas of PAM2
$\dot{P}_1$	-	Change rate of pressure PAM1
$\dot{P}_2$	-	Change rate of pressure PAM2
P_{atm}	-	Atmospheric pressure
P_{cr}	-	Critical pressure ratio
P_s	-	Supply pressure
Pa	-	Pascal
PAM	-	Pneumatic artificial muscle
PD	-	Proportional and derivative

PI	-	Proportional and integral
PID	-	Proportional-integral-derivative
Q_1	-	Volume flow rate of PAM1
Q_2	-	Volume flow rate of PAM2
$\overline{R}$	-	Air constant
s	-	Second
SISO	-	Single-input and single-output
SMC	-	Sliding-mode control
T	-	Temperature of gas
T_r	-	Rise time
T_s	-	Sampling time/settling time
µm	-	Micrometre
u_c	-	Control signal
U	-	Input signal
v	-	Volume rate of PAM
V_0	-	Initial PAM volume
V_1	-	Volume of gas of PAM1
V_2	-	Volume of gas of PAM2
V	-	Volt
ω_n	-	Natural frequency
x	-	Displacement of the mover
x_0	-	Initial position
$\dot{x}$	-	Velocity
$\dot{x}_r$	-	Reference rate

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Tang, T.F., Chong, S.-H., Mohd Nor, R., and Sato, Kaiji, 2019. Practical Control Strategy for Positioning Control of Pneumatic Artificial Muscles Driven Stage: Improved NCTF Control. *IEEE Access*, 7, pp. 85513-85524.

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