PRECISION MOTION AND ENERGY EXCHANGE CONTROL ON ROBOT'S LEG INTERACTION WITH SOFT SURFACE

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ABSTRAK

Pelbagai idea telah dibentangkan dalam membangunkan rekabentuk robot berasaskan rupa biologi makhluk hidupan sebenar seperti robot berkaki, robot terbang, robot berenang dan lain-lain. Dalam pembangunan sistem kawalan dan mekanisma rekabentuk robot berkaki, faktor keseluruhan kestabilan sistem mestilah diambil kira dan bukan sahaja faktor manipulasi dibahagian kakinya. Walau bagaimanapun kestabilan manipulasi sistem kaki robot ini tetap menjadi menjadi keutamaan dan asas untuk menjamin kestabilan sistem keseluruhan robot. Salah satu cabaran dalam kawalan manipulasi pada setiap kaki robot berkaki adalah untuk mengekalkan ketepatan gerakan sudut setiap sendi kakinya. Keperluan sistem kawalan yang mantap menjadi lebih tinggi dengan peningkatan bilangan darjah kebebasan setiap kaki robot dimana penyelarasan yang tepat diperlukan dalam ruang kerja kaki tersebut. Selain itu, faktor tidak linear dalam gerakan kaki robot juga perlu ditangani untuk memastikan kestabilan dinamik keseluruhan robot berkaki terutama ketika berjalan di kawasan yang tidak rata. Kaedah yang popular seperti kawalan impedans telah digunakan secara meluas dengan memahami interaksi dinamik diantara tapak kaki robot dan permukaan persekitaran yang hendak dipijak. Kebanyakan usaha penyelidikan telah tertumpu kepada kawalan dinamik yang dapat menempatkan semula kedudukan kaki robot semasa berjalan dikawasan berpermukaan yang tidak rata dan keras. Kaedah ini mungkin tidak sesuai untuk permukaan lembut yang memerlukan kaki robot untuk menahan medium sambil menolak badannya walaupun penyesuaian pada ketegangan permukaan telah dilakukan. Akibatnya, robot berkemungkinan besar akan terbalik atau terjatuh kerana kaki robot akan tergelincir berfaktorkan daripada tenaga yang rendah yang digunakan oleh setiap kaki robot tersebut. Oleh itu, di sini terdapat dua kenyataan masalah yang dapat diklasifikasikan iaitu implikasi pada ketidaktepatan gerakan sendi kaki dan pertukaran tenaga tak terkawal dalam gerakan dinamik kaki robot tersebut. Oleh itu, kajian tesis ini telah mengambil inisiatif untuk mencadangkan dua penyelesaian untuk isu-isu yang disebutkan di atas iaitu sistem kawalan *Propotional Integral-Antiwindup-Fuzzy Logic-Derivative* (PIA-FLC-D) untuk ketepatan gerakan setiap sendi kaki robot dan kawalan impedans untuk kestabilan dinamik kaki robot. PIA-FLC-D dicadangkan untuk mengatasi ketepatan bersama kaki yang terjejas oleh faktor graviti yang tidak linear. Kawalan impedans dikira dan diperolehi untuk memenuhi pembentukan halaju yang sesuai secara tidak langsung kepada pertukaran tenaga kaki yang dikhususkan pada setiap heretan kaki robot. Dalam kajian ini *Hexapod-to-Quadruped* (Hexaquad) robot digunakan sebagai sistem sasaran dalam mengesahkan teori-teori sistem kawalan yang dicadangkan. Merujuk kepada beberapa eksperimen yang telah dibuat, cadangan sistem kawalan PIA-FLC-D yang telah menunjukkan keputusan yang sangat baik dengan kelewatan masa hanya 0.1 saat berbanding sistem kawalan sebelumnya yang mengalami kelewatan masa 0.25 saat ketika kawalan ketetapan kaki. Bagi kes eksperimen terhadap cadangan kawalan impedans, keputusan menunjukkan bahawa kelajuan pergerakan kaki Hexaquad robot meningkat dengan daya yang dikenakan pada kedudukan menegak dan secara tidak langsung menyebabkan tenaga meningkat pada kaki tanpa mengubah bentuk asal pergerakan kaki robot tersebut. Dengan menggunakan kaki Hexaquad robot yang sama, ianya diuji diatas permukaan lembut (pasir) dan dalam pada masa yang sama, menanggung berat badan robot. Hasil keputusan menunjukkan ketika fasa mengheret, dengan mengunakan cadangan kawalan impedans, setiap sendi pada kaki tersebut mampu mengikut gerakan rujukan dengan tepat berbanding jika tidak menggunakannya.

ABSTRACT

Nowadays, various ideas have been presented in developing bio-inspired robot such as legged, flying, swimming and other crawling mechanisms. Generally legged robot development and control covered beyond manipulation issues in which stability of the overall system need to be catered as well. Stable leg manipulation for a legged robot becomes a priority to guarantee the whole system stability. One of the challenges in legged robot manipulation control is to sustain the leg's joint angular motion precision. As the number of degrees of freedom for a leg is increased, the demand for robust control becomes higher since it requires precise coordination in foot workspace. Besides that, the nonlinearity factor in robot's leg motion also need to be tackled to ensure the overall stability of a legged robot especially during walking on uneven terrain. Popular method such as impedance control has been extensively used by understanding dynamic interaction between leg tips and the environment. Most of the researched had emphasized on dynamic control that is able to reposition robot's foot placement during walking on the unstructured terrain with hard surfaces. This method may not be suitable for soft surface that required robot's leg to withstand the ground medium while pushing its body although repositioning was done. As a result, the overturning may happen to the robot since the robot's foot will slip due to the low energy to adapt with environment surface stiffness. Here, there are two problem statements which are implication of imprecision of leg joint motion and uncontrollable energy exchange in foot dynamic motion. Therefore, this study has taken initiative to propose two solutions for the aforementioned issues which are hybrid Proportional Integral-Antiwindup-Fuzzy Logic Control-Derivative (PIA-FLC-D) and impedance control respectively. PIA-FLC-D is proposed to overcome leg's joint precision affected by nonlinear gravitational factor. On the other hand, impedance control is derived to cater the velocity shaping as indirectly controlling the energy exchange of the leg specifically at leg dragging period. A bio-inspired robot named Hexapod-to-Quadruped (Hexaquad) robot is used as the targeted platform for verification and validation. The proposed PIA-FLC-D was verified and the results were compared with the predecessor controllers. The results show that PIA-FLC-D performs fast response with only 0.1s delay compared to its predecessor controller with 0.25s delay during trajectory tracking. For the case of the impedance control, the results show that Hexaquad's leg velocity increases with the contact force on vertical position in which resulting energy increased on the leg while maintaining the overall leg motion shape. The same Hexaquad's leg that applied the proposed impedance controller also tested completing the walking motion on the soft surface medium (dry sand) while bearing the robot's body weight. The results showed that during drag sequence, by using the proposed controller, each joint of Hexaquad's leg manage to follow the reference motion precisely compared to without using the proposed controller.

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LIST OF SYMBOLS

W_T	Total Weight
W_R	Robot Weight
W_p	Payload Weight
$u(t)$	Control Output
θ_n	n-Joint
θ_{f_n}	n-Joint Feedback
$\dot{\theta}$	Joint Velocity
$\ddot{\theta}$	Joint Acceleration
$\dot{\theta}_f$	Feedback Joint Velocity
$\ddot{\theta}_f$	Feedback Joint Acceleration
F_{ext}	External Force
F_{z_f}	Feedback Force on z-axis
F_{z_r}	Force Reference on z-axis
F_R	Force Reference
e_f	Force Error
Δs	Position state
$\Delta \dot{s}$	Velocity State
$\Delta \ddot{s}$	Acceleration state
T_{drag}	Drag Period
T_{swing}	Swing Period
V_{swing}	Swing Velocity
V_{drag}	Drag Velocity
TT	One Full Cycle
s_o	Width of pattern
h_o	Height of pattern

d_k	Actuator length
a_n	n-link length
τ_n	n-joint Torque
$(xyz)_o$	Initial starting point of walking motion
$(OXYZ)_o$	Origin on Cartesian
e_{θ_n}	Angular joint error
$\delta(t)_n$	PI-antiwindup controller output
$u(t)_n$	current control output
$u(t-1)_n$	previous value of control output
T_s	sampling time gain
K_I	proportional gain
K_P	integral gain
K_T	antiwindup gain
J_{v_n}	Jacobian for link linear velocity
J_{ω_n}	Jacobian for link rotational velocity
E_K	Kinetic Energy
E_P	Potential Energy
I_{comp}	Inertia component
$G(\theta)$	Gravity vector
ζ	Damping ratio
ΔT_{swing}	Swing motion rate of change
ΔT_{drag}	Drag motion rate of change

LIST OF ABBREVIATIONS

2D	Two Dimensional
COG	Centre of Gravity
COM	Centre of Mass
COP	Centre of Pressure
DOF	Degree of Freedom
FLC	Fuzzy Logic Control
FTG	Foot to Gripper
MFC	Model Following Control
NN	Neural Network
PI	Proportional Integral
PIA	Proportional Integral Antiwindup
PID	Proportional Integral Derivative
PIA-FLC	Proportional Integral Antiwindup-Fuzzy Logic Control
PIA-FLC-D	Proportional Integral Antiwindup-Fuzzy Logic Control-Derivative
POS	Polygon of Support
SEA	Series of elastic actuator
SISO	Single Input Single Output
UGV	Unmanned Ground Vehicle

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