UNIVERSITY OF TECHNOLOGY, SYDNEY

Design of a Parallel Shoulder Assistive Robot with Pneumatic Muscle Actuators

by

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Declaration of Authorship

I, Ruiyi Tang, declare that this thesis titled "Design of a Parallel Shoulder Assistive Robot with Pneumatic Muscle Actuators" and the work presented in it are my own. I confirm that:

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Abstract

Given the increasing stroke incidence and ageing population, robotic assistance for people suffering from physically weak upper limbs in their activities of daily life (ADL) is becoming more promising. However, most of the current upper limb assistive robots (or upper limb exoskeletons) are bulky and heavy when designed to meet the requirements of sufficient degrees of freedom (DoFs), workspace and joint torques. The objective of this thesis is to develop dynamic models of pneumatic actuators and design a new mechanism towards developing a compact and lightweight upper limb exoskeleton, while providing proper kinematic capability to assist a human's upper limbs in their ADL.

This research first focused on parallel mechanisms given their advantages of compactness and high stiffness. Multiple parallel mechanisms are reviewed in terms of their capability in delivering 3D rotational motion and safety concerning the forces transmitted to the shoulder joint when mechanisms are applied as a shoulder joint. Then, a *3UPU wrist* mechanism is selected given its superior kinematic capability. An alternative forward kinematics solution for the *3UPU wrist* mechanism is presented so that the upper limb's orientation can be estimated using the universal joint's rotation angles on the base, rather than measuring the mechanism's limb length.

Pneumatic muscle actuators (PMAs) are then selected for driving the robotic exoskeleton because of their superiority of high strength-to-weight ratio and inherent elasticity. An enhanced dynamic force model is developed to depict the PMA's nonlinear relationship between its length, pressure and external load. By introducing a model of Coulomb friction element, this dynamic force model overcomes the problems related to the current over-simplified models. The improvement of this enhanced model is evidently witnessed in situations where softer and more elastic PMAs are pressurised to perform large contractions.

A *3UPU wrist* mechanism test rig that can measure the universal joint angles is developed for verifying the mechanism's inverse kinematics and the proposed alternative forward kinematics. Experimental results validated the inverse kinematics of this mechanism in most cases and verified the solutions of platform orientation obtained from the alternative forward kinematics. A prototype exoskeleton is developed based on the *3UPU wrist* mechanism, and is used to test the performance of the PMAs and the *3UPU wrist* mechanism. A proportional–integral (PI) controller is used for the PMA position control. Two basic ADL movements are tested on the prototype. The experimental results and future work are then discussed.

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Abbreviations

ADL	Activities of Daily Life
CVT	Continuously Variable Transmission
DoF(s)	Degree(s) of Freedom
EAP	Electroactive Polymer
IMU	Inertial Measurement Unit
PI	Proportional–integral (Controller)
PID	Proportional–integral–derivative (Controller)
PMA/PM Actuator	Pneumatic Muscle Actuator
PWM	Pulse width modulation
ROM	Range(s) of Motion
SMA	Shape Memory Alloy
2D	Two dimensional
3D	Three dimensional
3UPU	Three Universal-Prismatic-Universal joint limbs (Mechanism)
nSPS+S	*n* Spherical-Prismatic-Spherical joint limbs plus one passive Spherical joint (Mechanism)
3RRR	Three Revolute-Revolute-Revolute joint limbs (Mechanism)
3RPS	Three Revolute-Prismatic-Revolute joint limbs (Mechanism)
3UPS+S	Three Universal-Prismatic-Spherical joint limbs plus one passive Spherical joint (Mechanism)
3UPU wrist	Three Universal-Prismatic-Universal joint limbs pure rotational (Mechanism)

Nomenclature

General Style

$\{O_A:X_AY_AZ_A\}$	Coordinate frame with origin at point O_A and axis X_A, Y_A, and Z_A
$\dot{l},\ddot{l}$	Differentiation and quadratic differentiation of a variable
$\vec{l}$	Vector
$\vec{l}^{\{O\}}$	Vector $\vec{l}$ in coordinate frame $\{O\}$
$\lvert\cdot\rvert$	Absolute value
$\lVert\cdot\rVert$	Vector length and normalised vector
$\angle O_1O_AA_i$	Angle between vector $\overrightarrow{O_1O_A}$ and $\overrightarrow{O_AA_i}$ at point O_A
$\cdot^T$	Transpose of a matrix
δL, $\delta\theta$	Virtual displacement, virtual rotation angle
$\partial\theta$	Partial derivative of variable θ
$P(t)$	Variable P as a time dependent

Specific Symbol Usage for 3UPU Wrist Mechanism

Geometric Points

O, O_A, O_B	The intersection point of the revolute pairs' axes from both the platform and the base, from the base, and from the platform in the *3UPU wrist*, respectively
A_i, B_i ($i = 1, 2, 3$)	Rotation centre of universal joints on the base and platform connected to the i^{th} limb, respectively
O_1, O_2	Plane centre (circular centre) of the base and platform plane, respectively

Geometric Constants and Variables

r_A, r_B	Length of $\lvert A_iO_1\rvert$ and $\lvert B_iO_2\rvert$, respectively
h_A, h_B	Distance from rotation centre O to the circular centre of base O_1 and O_2

	platform plane, respectively
θ_x, θ_y, θ_z	Rotation angles of the platform relative to the base at point O, around X, Y and Z axis, respectively
$\vec{\omega} = (\omega_x, \omega_y, \omega_z)$ $\vec{\eta} = (\eta_x, \eta_y, \eta_z)$	Angular velocity and angular acceleration of the platform
θ_{xAi}, θ_{yAi}	Rotation angles in the i^{th} universal joint on the base around axis X_{Ai} and axis Y_{Ai}, respectively
ω_{xAi}, ω_{yAi}	Angular velocity in the i^{th} universal joint on the base around axis X_{Ai} and axis Y_{Ai}, respectively
l_i	Length of the i^{th} limb

Coordinate Frames

$\{O_A\}$, $\{O_B\}$	Coordinate frame with origin at point O_A and O_B, attached to the immobile base and moving platform, respectively
$\{A_i: X_{Ai}Y_{Ai}Z_{Ai}\}$	Immobile that is attached to immobile part of the ith universal joint that is adjacent to the base.
$\{O_{Ai}:X_{OAi}Y_{OAi}Z_{OAi}\}$	mobile that is attached to the moving part of the ith universal joint that is adjacent to the base.

Matrices

R, R_x, R_y, R_z	Rotation matrix from platform to base, rotation matrix for around X, Y and Z axis alone, respectively
R_{OAi}	Rotation matrix from coordinate frame $\{A_i\}$ to frame $\{O_{Ai}\}$
R_{Ai}	Rotation matrix from coordinate frame $\{O_A\}$ to frame $\{A_i\}$
J	Jacobian matrix
$\vec{l}_i$, $\vec{s}_i$	The vector representing the i^{th} limb part and unit vector in the same direction, respectively
Φ	Objective function index of workspace optimisation

Specific Symbol Usage for PMA

$F(x, P)$	PMA force determined by variable contraction length x and pressure P

$F_{static}(x, P)$	Static PMAA force determined by variable contraction length x and pressure P
$F_{ce}(P)$	Force exerted by the contractile element
$F_{adjust}(x)$	Adjustment force added on static force to eliminate estimation error
$F_{coulomb}(x)$	Coulomb friction force
$F_{Damp}(x)$	Damping force
$x(t)$, $\dot{x}(t)$, $\ddot{x}(t)$	Contraction length, linear contraction velocity and contraction acceleration
$L(t)$	Length of the PMA
$D(t)$	Diameter of the PMA
L_0	Normal length of the PMA
$P(t)$	Pressure in the i^{th} PMA
$K(x, P)$	Stiffness of spring element parameterised by contraction length and pressure
K_1, K_2	Coefficients of stiffness of spring element
S_1, S_2, S_3	Coefficients of passive element
C_1	Coefficients of contractile element
N_1, N_2, N_0	Coefficients of Coulomb friction force
D_1, D_2	Viscous damping friction force coefficient
b	Total length of the outer mesh threads of the PMA
n	Turns of threads of the outer mesh of the PMA
μ	Viscosity of air gas
$v(t)$	Velocity of air