DESIGN OF SPHERICAL WRIST AND TRAJECTORY SOLUTION FOR ROBOTIC ARC WELDING APPLICATION

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THIS THESIS IS SUBMITTED IN FULFILLMENT FOR THE MASTER DEGREE OF SCIENCE (MECHANICAL ENGINEERING)

SCHOOL OF ENGINEERING
AND INFORMATION TECHNOLOGY
UNIVERSITI MALAYSIA SABAH
2007

UNIVERSITI MALAYSIA SABAH

BORANG PENGESAHAN STATUS TESIS@

JUDUL : DESIGN OF SPHERICAL WRIST AND TRAJECTORY SOLUTION FOR ROBOTIC ARC WELDING APPLICATION
IJAZAH : SARJANA SAINS (KEJURUTERAAN MEKANIKAL)

SESI PENGAJIAN : 2004-2007

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CATATAN : @ Tesis dimaksudkan sebagai tesis Ijazah Doktor Falsafah dan Sarjana secara penyelidikan atau disertassi bagi pengajian secara kerja kursus dan penyelidikan, atau laporan Projek Sarjana Muda (LPSM).

DECLARATION

The materials in this thesis are original except for quotations, excerpts, summaries and references, which have been duly acknowledged.

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ACKNOWLEDGEMENTS

Life is amazing. It is just like a roller coaster ride that excites us. However, most of the time, we are down at the ramp waiting for the height that gives us the "wow" effect and that engraves deeply in our heart. The easy time comes so fast while hard time stays too long to be felt. Thanks God for calming my monkey mind and giving me the strengths to handle all the events, which slowly enlighten the meaning of my life as a subset to this system. Therefore, reflecting ourselves into others position is important to fully understand a matter as well as to live in respectfulness and harmony. I am feeling lucky to be able to complete this Master degree project. The success of this project is the outcome of accumulated contributions from many individuals and organisations, either directly or indirectly.

I, hereby, would like to express my gratefulness to my supervisor, Associate Professor Dr. Yeo Kiam Beng for his guidance and helping hands. His responsive, determinative and tireless characteristic in work does give me a good example. Thank you and wish you are always in pink health to achieve the world's best.

Second, I would like to acknowledge the contribution from the Yayasan Universiti Malaysia Sabah (UMS) for granting a scholarship to me. This scholarship does cover most of my expenses and consistently funding me, which has put me in mind-free of financing problems after an initial 5 months struggle. I am glad of it and my only return is the efforts I have put in to ensure its worthiness.

Acknowledgements are also due to my close buddies in Universiti Malaysia Sabah, particularly to "Dai Lou" (Choong Wai Heng), Datuk (Lim Eng Har), and Bob (Mohd Aidy Faizal) for sharing and enjoying the good and bad together during this period. Also, I wish to express my thankfulness to all my best friends that are supporting me all the way over the years. Thank you very much.

Not to forget are the friendly staffs of Postgraduate Centre, particularly to Miss Sharifah and Puan Rozaidah, who have entertained all my questions and requests with a smile during my two-and-a-half year of studentship. This excellent service is hard to be found elsewhere. All the best and keep the good work.

My very special thank attributes to my dearest family and the only lovely partner. Without your concerns and unconditional supports, I may not be able to manage everything as strong and smooth as I am. I appreciate you presence as a part of my life. This work is dedicated to you.

Last but not least, to those people who have directly or indirectly helped me but omitted here, I apologise. Your helps do bring meanings to me. Thanks. I should also apologise to those who I have intentionally or unintentionally caused hurt by my words or actions.

Thank you.

CHUA BIH LII
MAY 2007.

ABSTRACT

This thesis centred on designing a three degree-of-freedom (3-DOF) spherical wrist subassembly. This wrist subassembly was integrated with a concurrent 3-DOF arm subassembly project to form a complete arc welding robot assembly capable of handling 6 kilogram payload called Robotums RA-01 in the Universiti Malaysia Sabah (UMS). This was done by first determining the design goal via a design framework that had been laid out to allow design independency in which all required information for design is shared for easing the concurrent works and promoting the reuse of design with different configurations in the future. The functional kinematic structure for the Robotums RA-01, which has the similar robot configuration to other typical arc welding robots, and the mechanism in the wrist subassembly were formed and analysed. The torch tip position and orientation was mapped from and to the corresponding robot joint angles via the forward and inverse kinematic respectively with the aid of 4×4 transformation matrix. The kinematics model was implemented and verified by a double number precision program with the negligible computational error of less than 5.0×10^{-13} degree for the joint-to-Cartesian-to-joint space transformations using joint angles input in degree unit. The wrist orientation error increases when joint angle 6 was approaching zero from absolute one degree, but still acceptable for arc welding application. Besides, the wrist singularity occurred due to the joint angle 6 was investigated computationally. Meanwhile, the wrist kinematics analysis was performed by using the fundamental circuit and coaxiality condition to reveal the relationship between the actuator and joint space parameters. The concept of fundamental circuit was extended to cater for ready-made drive reduction unit by introduction of the equivalent fundamental circuit. Besides, the static analysis for the wrist mechanism was performed using virtual work method to determine the torque relationship between the joints and the actuators. Then, iterative selection of transmission drive ratio for harmonic drives, timing belts and miter gears as well as actuators was exercised to meet the torque and speed requirement before the functional kinematic structure of the wrist subassembly can be transformed into a virtual CAD solid model using SolidWorks 2005 that details the transmission elements with all the necessary bearings, seals and mountings and includes a standard mechanical plate interface, wire feeder mounting points and cable bending space in between the upper arm links. Several critical parts in the wrist subassembly were ensured not to be failed under normal loadings using CosmosWorks 2005 and by manual calculations. With the weight and moment of inertia of the transmission elements being computed by the CAD program, the selection of actuators was validated at the end of the wrist subassembly design process. Finally, this thesis proposed an arc welding trajectory planning algorithm for stationed typical 6-DOF industrial robot configuration that capable to generate the torch frame automatically for a specified straight trajectory and extendable for arc or circular trajectory with correlation to the torch speed, height and angles without collision. These torch frames were interpolated along the Cartesian path and the robot joints trajectory were planned using cubic polynomial interpolation scheme.

ABSTRAK

DESIGN OF SPHERICAL WRIST AND TRAJECTORY SOLUTION FOR ARC WELDING APPLICATION

Tesis ini tertumpu kepada reka bentuk suatu pergelangan yang mempunyai tiga darjah kebebasan (3-DOF) dalam bentuk sfera untuk melengkapi robot kimpalan arka Robotums RA-01 di Universiti Malaysia Sabah yang berkemampuan mengendalikan beban seberat enam kilogram. Sebagai permulaan, satu rangka rekaan dibentuk bagi menetapkan matlamat reka bentuk untuk memudahkan kerja serentak dan integrasi semula rekaan ini dengan konfigurasi lengan yang berbeza di masa depan. Struktur kinematik berfungsi bagi Robotums RA-01 yang mempunyai tatarajah setara dengan robot kimpalan arka yang lain, serta mekanisma dalam pergelangan dibentuk dan dianalisis. Hubungan di antara posisi dan haluan mata alat pengimbal dengan sudut sambungan robot diperolehi melalui analisis kinematik ke-depan dan ke-belakang dengan bantuan matriks transformasi 4×4 di mana ia telah digunakan dalam program berkejituan nombor "double" dan menghasilkan ralat pengiraan komputer tidak melebihi 5.0×10^{-13} darjah dalam pengubahan dari sudut sambungan robot ke satah Cartesian dan kembali ke sudut sambungan robot. Ralat haluan pergelangan meningkat apabila sudut sambungan robot keenam menghampiri sifar dari nilai mutlak satu darjah, tetapi masih boleh diterima untuk aplikasi kimpalan arka robotik. Melalui pengiraan komputer, singulariti pergelangan yang berlaku disebabkan oleh sudut sambungan robot keenam turut dikaji. Analisis kinematik pergelangan turut dijalankan untuk mengenalpasti hubungan di antara satah pemacu dan sambungan robot dengan menggunakan litar asas dan keadaan sepaksi. Konsep litar asas dikembangkan kepada litar asas setara untuk menghubungkaitkan hubungan input-output bagi sistem gear siap sedia. Selain itu, analisis statik bagi mekanisma pergelangan turut dijalankan melalui konsep kerja maya untuk mengetahui hubungan tork di antara pemacu dan sambungan robot. Kemudian, nisbah sistem gear untuk "harmonic drive", tali sawat bergigi dan gear serong dipilih secara lelaran bagi memenuhi keperluan tork dan kelajuan sebelum struktur kinematik berfungsi tersebut dikembangkan dalam bentuk model maya berjasad padu menggunakan SolidWorks 2005 di mana perincian dibuat ke atas komponen sistem gear berserta semua galas unsur guling, pengedap minyak dan tapak sambungan, serta kelengkapan plat sambungan alat, lokasi sokongan mesin penyuap wayar dan struktur lengan atas berkembar. Beberapa komponen kritikal di bawah beban normal dianalisis menggunakan CosmosWorks 2005 dan pengiraan manual. Berasaskan jisim dan jisim momen inersia yang dikira oleh program CAD, pemacu yang dipilih disahkan mampu berfungsi pada akhir proses rekaan. Akhirnya, tesis ini mengetengahkan susunatur bagi perancang trajektori kimpalan arka untuk 6-DOF robot industri berstesen tetap yang boleh menjana paksi alat pengimbal secara automatik dengan mengambilkira kelajuan, tinggi dan sudut alat pengimbal tanpa perlanggaran. Paksi alat pengimbal diinterpolasikan mengikut lokus kimpalan dan seterusnya, sudut sambungan robot dirancang menggunakan polinomial darjah ketiga.

KEYWORDS

Robotic arc welding, robot kinematics, wrist mechanism, trajectory planning algorithm

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LIST OF ABBREVIATIONS

ABICOR	Alexander Binzel Corporation
AC	Alternating current
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineering
AWS	American Welding Society
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CO_2	Carbon dioxide
CP	Continuous path
CPU	Central Processing Unit
DE	Distortion energy
DOF	Degree of freedom
DTPS II	Desk Top Programming and Simulation System Version 2
e.g.	For example
ESAB	Elektriska Svetsningsaktiebolaget
etc.	Etcetera
FCAW	Flux cored arc welding
GDP	Gross Domestic Product
GMAW	Gas metal arc welding
GTAW	Gas tungsten arc welding
i.e.	That is to say
IFR	International Federation of Robotics
ISO	International Standard Organisation
JETRO	Japan External Trade Organization
KHK	Kohara Gear Industry

MAG	Metal Argon Gas
MIG	Metal Inert Gas
n.d.	No date
PAW	Plasma arc welding
PC	Personal Computer
PLC	Programmable Logic Controller
ppr	Point per revolution
PTP	Pose-to-pose
rpm	Revolution per minute
RSS	Root sum of squares
SCARA	Selectively Compliant Arm for Robotic Assembly
SDP/SI	Stock Drive Products/Sterling Instrument
SMAW	Shielded metal arc welding
SRAC	Structural Research and Analysis Corporation
TCP	Tool centre point
UNECE	United Nations Economic Commission for Europe

LIST OF SYMBOLS

$\dot{q}$	Joint rate
$\dot{\theta}$	Joint rate for revolute joint
$\dot{d}$	Joint rate for prismatic joint
$\dot{\mathbf{x}}$	Velocity vector-matrix in Cartesian space
$\boldsymbol{\varphi}$	Actuator input
$\sqrt{a}$	Heywood's parameters
λ	Longitudinal angle of welding torch/ Travel angle of welding torch
φ	Transverse angle of welding torch
ρ	Mass density of the electrode material
ϕ	Angle between mid-plane and plane determined by the electrode and weld axes
γ	Angle between electrode axis and z-axis weld frame
ω or ω	Angular velocity vector
ξ_1	Fraction of proof stress felt by the bolt when tightened
$\perp$	Perpendicular to
A	Cross sectional area
a_i	Link length of joint i
A_t	Tensile stress area on bolt's threat
C	Centre distance between two pulleys or gears
c_i	Short-hand notation for Cosine θ_i
D	Difference between number of teeth on larger and smaller pulleys
d_i	Joint offset of joint i
D_t	Torch tip diameter
E	Centre distance factor
F	Force
f	Wire feed rate

F'	Primary shear force
F''	Secondary shear force
f_i	Number of relative degrees of freedom permitted by joint *i*
F_i	Preload Force
f_u	Update rate
h	Torch height
${}^{i-1}\mathbf{d}_i$	3×1 vector-matrix between the origins of frame *i* with respect to frame *i*-1
${}^{i-1}R_i$	3×3 rotation matrix between the axes of frame *i* with respect to frame *i*-1
${}^{i-1}T_i$	4×4 transformation matrix of frame *i* with respect to frame *i*-1
I_z	Mass moment of inertia about Z-axis
J	Polar moment of inertia
k	Number of via points
k_a	Surface condition modification factor
k_b	Size modification factor
k_c	Load modification factor
k_d	Temperature modification factor
k_e	Miscellaneous effects modification factor
KE	Kinetic energy
K_f	Fatigue stress concentration factor under bending/axial load
K_{fs}	Fatigue stress concentration factor under torsional load
K_t	Stress concentration factor under bending/axial load
K_{ts}	Stress concentration factor under torsional load
L	Belt length
L	Lagrangian
l_c	Length from weld frame to the collision point C
M	Mobility of the mechanism
M	Moment

M_z	Moment about the rotation axis Z
N	Gear ratio
n	Number of teeth; or Number of joint
n_c	Number of cap screw
O_i	Origin of coordinate system at joint i
$\mathbf{p}$	Positional vector
P	Power
p	Pitch
PE	Potential energy
q_i	Joint variable of joint i
R	Notation for revolute joint
R	Harmonic drive rated reduction ratio
r	Radius; or Stress ratio
r_{crit}	Critical stress ratio
$R_{i,j}$	Rotation matrix for j angle about i axis
s	Length of the welding joint
S	Length of welding joint
S_e	Endurance limit of a location of a machine part
S_e'	Rotary beam endurance limit
s_i	Short-hand notation for Sine θ_i
S_p	Proof strength
S_{ut}	Ultimate strength
S_y	Yield strength
$T_{i,j}$	Basic transformation matrix for rotational transformation about axis i at j angle or translational transformation along axis i at j distance
V	Shear reaction
$\mathbf{V}$ or v	Linear velocity vector; or Torch speed
W	Work done

x_i	x-axis of coordinate system at joint *i*, or *x*-coordinate of point P_i
y_i	y-axis of coordinate system at joint *i*, or *y*-coordinate of point P_i
z_i	z-axis of coordinate system at joint *i*, or *z*-coordinate of point P_i
$\mathbf{z}_i$	Unit vector along the axis of joint *i*
α	Angular acceleration, or Metal transfer efficiency
α_i	Twist angle of joint *i*
β	Torch bend angle
η	Efficiency
θ_i	Joint angle of joint *i*
ξ	Actuator input torques
σ	Stress
σ'	Von Mises stress
τ	Torque
τ_s	Shear strength
χ	Angle between the bisection plane on two adjacent surfaces

(Note that vectors are represented in lowercase bold letters and matrices are in uppercase italic letter)

GLOSSARY

Extracted from American Welding Society's publication ANSI/AWS A3.0-9X, Standard Welding Terms and Definitions, Draft 4, dated November 1993.

Term	Definition
Adaptive control welding	Welding with a process control system that automatically determines changes in welding conditions and directs the equipment to take appropriate action.
Arc length	The distance from the tip of the welding electrode to the adjacent surface of the weld pool.
Arc spot weld	A spot weld made by an arc welding process.
Arc time	The time during which an arc is maintained in making an arc weld.
Arc voltage	The voltage across the welding arc.
Arc welding deposition efficiency	The ratio of the weight of filler metal deposited in the weld metal to the weight of filler metal melted, expressed in percent.
Arc welding gun	A device used to transfer current to a continuously fed consumable electrode, guide the electrode, and direct the shielding gas.
Arc welding torch	A device used to transfer current to a fixed welding electrode, position the electrode, and direct the flow of shielding gas.
Base metal	The metal or alloy that is welded, brazed, soldered, or cut.
Consumable electrode	An electrode that provides filler metal.
Depth of fusion	The distance that fusion extends into the base metal or previous bead from the surface melted during welding.
Duty cycle	The percentage of time during an arbitrary test period that a power source or its accessories can be operated at rated output without overheating.
Electrode extension	In flux-cored arc welding, electrogas welding, gas metal arc welding, and submerged arc welding, the length of electrode extending beyond the end of the contact tube; in gas tungsten arc welding and plasma arc welding, the length of tungsten electrode extending beyond the end of the collet.
Filler metal	The metal or alloy to be added in making a welded, brazed, or soldered joint.
Globular transfer	In arc welding, the transfer of molten metal in large drops from a consumable electrode across the arc.
MIG welding	A non-standard term for gas metal arc welding and flux-cored arc welding.
Seam weld	A continuous weld made between or upon overlapping members, in which coalescence may start and occur on the faying surfaces or may proceed from the outer surface of one member. The continuous weld may consist of a single weld bead or a series of overlapping spot welds.
Shielding gas	Protective gas used to prevent or reduce atmospheric contamination.
Spatter	The metal particles expelled during fusion welding that do not form a part of the weld.

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PENGAKUAN

Saya akui karya ini adalah hasil kerja saya sendiri kecuali nukilan dan ringkasan yang setiap satunya telah dijelaskan sumbernya.

8 Mac 2004

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