

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

**CHUA BIH LII**

- PERPUSTAKAAN  
UNIVERSITI MALAYSIA SABAH

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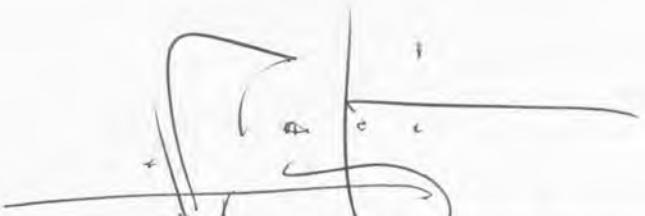
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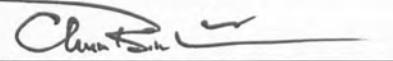


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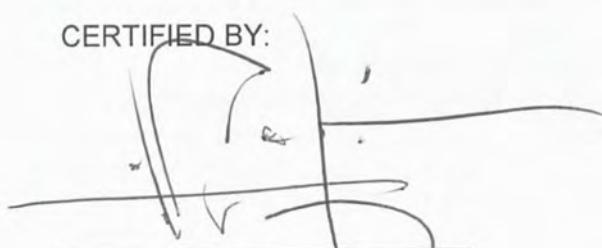
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## ABSTRACT

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  $4 \times 4$  transformation matrix. The kinematics model was implemented and verified by a double number precision program with the negligible computational error of less than  $5.0 \times 10^{-13}$  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  $4 \times 4$  di mana ia telah digunakan dalam program berkejituhan nombor "double" dan menghasilkan ralat pengiraan komputer tidak melebihi  $5.0 \times 10^{-13}$  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 penyuar 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

## CONTENTS

	Page
<b>TITLE PAGE</b>	ii
<b>DECLARATION</b>	iii
<b>ACKNOWLEDGEMENTS</b>	iv
<b>ABSTRACT</b>	v
<b>ABSTRAK</b>	vi
<b>KEYWORDS</b>	vii
<b>CONTENTS</b>	viii
<b>LIST OF TABLES</b>	xii
<b>LIST OF FIGURES</b>	xiii
<b>LIST OF ABBREVIATION</b>	xviii
<b>LIST OF SYMBOLS</b>	xx
<b>GLOSSARY</b>	xxiv
 <b>CHAPTER 1: INTRODUCTION</b>	 1
1.1 Overview	1
1.2 Prospect of Robotic Arc Welding	1
1.3 The Challenges of Robotic Arc Welding	4
1.4 Objective	6
1.5 Scope of Project	6
1.6 Methodology	7
1.7 Thesis Organisation	8
 <b>CHAPTER 2: LITERATURE SURVEY</b>	 11
2.1 Overview	11
2.2 Robotic Arc Welding System	11
2.3 The Past and Present of Robotic Arc Welding	13
2.4 Arc Welding Technology for Robot Application	19
2.4.1 Gas Metal Arc Welding (GMAW) Using Industrial Robots	20
2.4.2 Influencing Factors for Robotic GMAW	22
2.5 Robot Wrist	24
2.5.1 Wrist Structure and Configurations	25
2.5.2 Wrist Mechanism	27



	Page
2.6 Robot Kinematics	31
2.6.1 Positional Kinematics	31
2.6.2 Differential Kinematics	40
2.6.3 Wrist Kinematics	45
2.6 Trajectory Planning	46
2.7 Robot Dynamics	50
2.7.1 Dynamics Model for Links	51
2.7.2 Dynamics Model for Transmissions	55
2.8 Summary	56
<b>CHAPTER 3: WRIST CONCEPTUAL DESIGN</b>	<b>57</b>
3.1 Overview	57
3.2 Design Framework	57
3.3 Preliminary Design	60
3.3.1 Conceptual Design	60
3.3.2 Structure Representation of Robot and Wrist Mechanisms	62
3.3.3 Joint Torque Requirement	64
3.4 Summary	66
<b>CHAPTER 4: ROBOT KINEMATICS</b>	<b>67</b>
4.1 Overview	67
4.2 Positional Kinematics	67
4.2.1 Denavit-Hartenberg Convention	67
4.2.2 Forward Kinematic	72
4.2.3 Inverse Kinematic	77
4.3 Differential Kinematics	86
4.3.1 Geometric Jacobian	86
4.3.2 Geometric Jacobian for Typical Arc Welding Robot	89
4.4 Summary	92
<b>CHAPTER 5: KINEMATIC ANALYSIS OF WRIST MECHANISM</b>	<b>93</b>
5.1 Overview	93
5.2 Actuator-Joint Space Transformation for Wrist Mechanism	93
5.2.1 Fundamental Circuit and Coaxiality Condition	94
5.2.2 Harmonic Drive	95
5.2.3 Wrist Mechanism	97
5.3 Static Force Analysis of Wrist Mechanism	102

	Page
5.4 Summary	104
<b>CHAPTER 6: WRIST MECHANICAL DESIGN</b>	<b>105</b>
6.1 Overview	105
6.2 Selection of Mechanical Transmissions and Actuators	105
6.2.1 Determination of Drive Ratio	106
6.2.2 Torque Estimation and Selection of Transmissions	109
6.2.3 Selection of Actuators	124
6.3 Virtual Modelling and Analysis	128
6.3.1 CAD Modelling	128
6.3.2 CAE Analysis	134
6.4 Analysis of Critical Component	141
6.4.1 Shaft	141
6.4.2 Torque Tube	146
6.4.3 Socket Head Cap Screw	147
6.5 Torque Requirement Update and Design Conformity Check	149
6.6 Summary	152
<b>CHAPTER 7: WELDING TRAJECTORY PLANNING</b>	<b>153</b>
7.1 Overview	153
7.2 Welding Joint	153
7.3 Imposed Constraints for Arc Welding Robot	154
7.3.1 Torch Speed	155
7.3.2 Torch Height	155
7.3.3 Torch Approach Direction	156
7.4 Torch Rotation Matrix	157
7.5 Collision Avoidance Strategy	159
7.5.1 Critical Torch Angle	159
7.5.2 Prediction of Arm and Workpiece Collision	162
7.5.3 Torch Orientation Selection Priority	166
7.5.4 Inverse Kinematics Solution Selection Priority	169
7.6 Computation of Via Points Information	170
7.7 Joint Space Trajectory interpolation Scheme	174
7.8 Planning Algorithm	177
7.9 Trajectory Planning on Straight Welding Joint	179
7.10 Summary	181



	Page
<b>CHAPTER 8: RESULTS AND DISCUSSIONS</b>	<b>182</b>
8.1 Overview	182
8.2 Cartesian-Joint-Actuator Space Transformation Model	182
8.2.1 Cartesian-to-Joint Space Transformation	182
8.2.2 Joint-to-Actuator Space Transformation	184
8.2.3 Actuator-to-Joint Space Transformation	187
8.2.4 Joint -to-Cartesian Space Transformation	188
8.2.5 Wrist Singularity Analysis	194
8.3 Design of 3-DOF Spherical Wrist	196
8.4 Arc Welding Trajectory Algorithm	201
8.5 Summary	206
<b>CHAPTER 9: CONCLUSION AND FUTURE WORKS</b>	<b>207</b>
9.1 Overview	207
9.2 Conclusion	207
9.3 Future Works	209
<b>REFERENCES</b>	<b>211</b>
<b>APPENDICES</b>	<b>219</b>
A Various arc welding robot from major manufacturers	219
B Wrist subassembly configuration for various arc welding robot from major manufacturerers	221
C Current European and ISO standards regarding industrial robots	222
D Types of transmission used by various patented wrist mechanisms for industrial robot	223
E Exploded views of Robotums-R01's wrist subassembly	225
F Trigonometric identities	232
G Derived paper	233



## LIST OF TABLES

Table No.	Description	Page
1.1	2003 World metal consumption list	2
2.1	Influences of shielding gas in various area	23
2.2	Summary of effects due to welding parameters change	23
2.3	Several direct drive motors available in the market	28
2.4	Advantages and disadvantages of various robots' transmission	29
3.1	Degree of protection given by the IP number sequence	59
3.2	Harmonic drive configurations as a gear reduction unit	63
3.3	Torque requirement for 3-DOF wrist joints	65
4.1	Possible cases of frame assignment	69
4.2	Denavit-Hartenberg parameters of the arc welding robot	73
4.3	Sign of $p_x$ and $p_y$ for determination of quadrant of the arc tangent solution	80
4.4	Sign of resulting trigonometry for corresponding quadrants	83
6.1	Harmonic drive and its configuration being used in wrist mechanism	107
6.2	Summary of selected transmission detail	124
6.3	Load moment of inertia for each joint	126
6.4	Reflected moment of inertia at the input of each transmission	128
6.5	Restraints and loads imposed on shaft	135
6.6	Torque requirement update for 3-DOF wrist joints	150
6.7	Torque input for two static loading cases	151
7.1	Allowable transverse and longitudinal angles	162
7.2	Workpiece coordinate definition	180
8.1	List of computations required for forward kinematics functions	190
8.2	List of computations required for forward kinematics with grouped operations	191



<b>Table No.</b>	<b>Description</b>	<b>Page</b>
8.3	Wrist singularity configurations due to angle combinations of $\theta_2$ , $(\theta_3 + \theta_4)$ and $\theta_5$	195
8.4	Five different wrist configurations to investigate orientation errors	195
8.5	Accumulated errors at output of Harmonic Drives	198



## LIST OF FIGURES

Figure No.	Description	Page
1.1	Manufacturing Sector Contributions in Malaysia's GDP Year 1987 – 2005 (Source: Ministry of Treasury, Malaysia)	4
2.1	Robotic arc welding system	13
2.2	Arc welding family in the AWS Master Chart of Welding and Allied Processes	20
2.3	Process diagram of gas metal arc welding	20
2.4	Venn diagram of weldable base metal for GMAW and FCAW	21
2.5	Kinematic structure for a typical arc welding robot with spherical wrist	25
2.6	Singularity configurations	26
2.7	Frenet-Serret frame on (a) pipe and flat intersection, and (b) two pipes intersection	48
2.8	Forces and moments acting on link $i$	53
2.9	Lumped model of a single link with actuator and drive train	56
3.1	Position of the load relative to the mechanical interface	58
3.2	Kinematic structure of 6-DOF robot	62
3.3	Kinematic structure of 3-DOF spherical wrist mechanism	63
3.4	Kinematic representation for harmonic drive gearing	63
4.1	Denavit-Hartenberg frame assignment	69
4.2	Positive sense for $d_i$ , $\theta_i$ and $\alpha_i$	70
4.3	Successive frame rotation about (a) fixed frame, and (b) current frame	71
4.4	Frames assignment on robot with joint offset and link lengths being shown	74
4.5	Frame assignment from frame 7 to the tip of welding torch	76
4.6	Geometrical relationships between $p_x$ , $p_y$ and $\theta_2$	80
4.7	Geometrical relationships between $a_4$ , $d_5$ , $\theta_3$ and $\theta_4$	81
4.8	Linear velocity vector due to rotation at joint $i$	88



<b>Figure No.</b>	<b>Description</b>	<b>Page</b>
5.1	Kinematic structure of a fundamental circuit	94
5.2	Three links with a common rotation axis	95
5.3	Harmonic drive elements and its functional kinematic structure	96
5.4	Kinematic structure of 3-DOF spherical wrist mechanism with link numbering	98
6.1	Flow chart for selecting mechanical transmissions and actuators	105
6.2	Belt geometry	112
6.3	Type of idler	116
6.4	Simple gearing system	127
6.5	Isometric view of wrist subassembly	129
6.6	Centre of mass for the wrist subassembly as obtained from mass properties tool	129
6.7	Wrist A-A section view and mechanical interface dimensioning	131
6.8	A-A section view at elbow	131
6.9	B-B section view at wrist showing joint angle 6 during collision	132
6.10	Wrist workspace drawn using SolidWorks 2005	132
6.11	B-B section view at elbow showing motor cable routing through common link	133
6.12	Mounting for wire feeder and two tapered C-channel as upper arm	133
6.13	Robotums RA-01 with ABB welding torch attached	134
6.14	Mesh at the small fillet of the shaft	136
6.15	Factor of safety distribution on the shaft	136
6.16	Three cases of safety factor distribution on the upper arm-L	138
6.17	Static displacement of the upper arm-L under loading case (a)	139
6.18	Static displacement of the motor cover	140
6.19	Factor of safety distribution for the motor cover	140
6.20	Shaft (a) Dimension; (b) Free body diagram; (c) Moment diagram	142



<b>Figure No.</b>	<b>Description</b>	<b>Page</b>
6.21	Simply supported beam with overhanging load	146
6.22	Location of the socket head cap screws from C-C sectional view; and A-A sectional view	147
6.23	Centre of mass for rotating parts about axis $z_4$	149
6.24	Centre of mass for rotating parts about axis $z_5$	150
7.1	Five basic welding joints	154
7.2	Relative position of the weld with respect to robot reference frame	154
7.3	Torch frame governed by transverse and longitudinal angles	156
7.4	Torch frame assignment	157
7.5	Critical torch angle $\gamma_C$	160
7.6	Critical torch angle $\gamma_B$	161
7.7	Upper arm collision with workpiece	163
7.8	Position of the lowest allowable point D measured from the wrist centre	164
7.9	Lower arm collision with the workpiece	165
7.10	Torch orientation selection flowchart	168
7.11	Tree of inverse kinematic solutions with corresponding equation number	169
7.12	Robot arm configurations	169
7.13	Via points information built-up flowchart	173
7.14	Arc welding trajectory planning flowchart	178
7.15	User input interface	179
7.16	Torch angle selection result at selected via points	180
7.17	Joint angle against time graph	181
8.1	Transformation between Cartesian – joint – actuator space	182
8.2	Space transformation program	192
8.3	RSS errors due to rotation of Joint 2	192
8.4	RSS errors due to rotation of Joint 3	193

<b>Figure No.</b>	<b>Description</b>	<b>Page</b>
8.5	RSS errors due to rotation of Joint 4	193
8.6	Log-log graph for orientation RSS errors against Joint 6 angle	195
8.7	Location of gaskets and O-rings at the end link	197
8.8	Collision between workpiece and torch breakaway device	201
8.9	Equivalent workpiece to represent a curved workpiece	202
8.10	Torch orientations at all selected points	205



## 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 <sub>2</sub>	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
$\dot{x}$	Velocity vector-matrix in Cartesian space
$\varphi$	Actuator input
$\sqrt{a}$	Heywood's parameters
$\lambda$	Longitudinal angle of welding torch/ Travel angle of welding torch
$\varphi$	Transverse angle of welding torch
$\rho$	Mass density of the electrode material
$\phi$	Angle between mid-plane and plane determined by the electrode and weld axes
$\gamma$	Angle between electrode axis and z-axis weld frame
$\omega$ or $\omega$	Angular velocity vector
$\xi_1$	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 $\theta_i$
$D$	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
${}^{i-1}\mathbf{d}_i$	$3 \times 1$ vector-matrix between the origins of frame $i$ with respect to frame $i-1$
${}^{i-1}R_i$	$3 \times 3$ rotation matrix between the axes of frame $i$ with respect to frame $i-1$
${}^{i-1}T_i$	$4 \times 4$ 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 $\theta_i$
$S_p$	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 $i$
$\alpha$	Angular acceleration, or Metal transfer efficiency
$\alpha_i$	Twist angle of joint $i$
$\beta$	Torch bend angle
$\eta$	Efficiency
$\theta_i$	Joint angle of joint $i$
$\xi$	Actuator input torques
$\sigma$	Stress
$\sigma'$	Von Mises stress
$\tau$	Torque
$\tau_s$	Shear strength
$\chi$	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.

<b>Term</b>	<b>Definition</b>
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



WONG GING ZING  
HS2001-1654



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