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ADAPTIVE CONTROL OF WELD PENETRATION AND TRAJECTORY FOR ROBOTIC GTAW

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By

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LIST OF ABBREVIATIONS

a	Offset distance along X axis
$a(n)$	Approach vector
d	Distance along Z axis
e	Normalizing coefficient
$e(t)$	Error at time t
$n(n)$	Normal vector
$p(n)$	Position vector
q	Joint variable
$r(t)$	Desired reference input
s	Laplace transform converted time
$s(n)$	Sliding vector
t	Time, sec
t_b	Arc base time, sec
t_{cycle}	Cycle time, sec
t_p	Arc pulse time, sec
u	Distance
$u(i)$	Distance segment
$\bar{u}(n)$	Torch travel distance after n cycles
$v(t)$	Linear velocity
$W(n)$	D-H matrix of weld joint coordinate frame
$z(i)$	Vectors parallel to the world Z axis

B	Bead width, mm
B_m	Measured bead width, mm
B_{sp}	Calculated bead width, mm
Cos	Cosine
$C_o^{base}(t)$	4 by 4 matrix function of time describing the working coordinate frame of object
$D(\lambda)$	Drive matrix
Sin	Sine
F	Effective viscous friction
Fl	Load viscous friction
Fm	Motor viscous friction
F_s	Filler wire speed, in/min
Gl	Torque transfer function

I	Arc current, amps
I_b	Base current, amps
I_m	Average current, amps
I_p	Pulsed current, amps
J	Effective moment of inertia
$Jaco$	Forward Jacobean matrix
$J(\theta)$	Jacobean matrix
Jl	Load moment of inertia
Jm	Motor moment of inertia
J	Jacobean matrix
Kd	Derivative gain
Ki	Integrated gain
Kp	Proportional gain
L_a	Arc length, mm
M	Gear ratio
Pi	Point at 3D space
$P(u)$	Point coordinate in distance u
P	Penetration depth, mm
P_{base}^{obj}	4 by 4 matrix describing the desired gripping position and orientation of object
Pt	A point in 3D space
S_t	Torch speed, mm/sec
S_{td}	Desired welding speed
S_t^*	Transient welding speed
T	Total time for traversal of segment
T_s	Workpiece thickness, mm
T_0^6	4 by 4 matrix describing the manipulator hand position and orientation
T_6^{tool}	4 by 4 matrix describing the tool position and orientation
X	Length of vector

Φ	Angular position
$\dot{\Phi}$	Joint angular velocity
$\ddot{\Phi}$	Angular acceleration
$\Omega(t)$	Tool angular velocity
α	Link angle
β	Constant coefficient

λ	Normalized time
θ	Joint angle
$\dot{\vartheta}$	Joint velocity
$\dot{\theta}_a$	Actual joint velocity
$\dot{\theta}_d$	Desired joint velocity
τ	Torque
τ_l	Torque for load shaft
τ_m	Torque for motor shaft

keV	Kilo-electronvolt
kW	Kilo-watt
AC	Alternating current
AISI	American standard for steels
Al	Aluminium element
ASME	American Society of Mechanical Engineers
B/W	Black and White
C	Carbon element
CAD	Computer aided design
CAM	Computer aided manufacturing
CCD	Charge coupled device
CIM	Computer integrated manufacturing
Cu	Copper element
DC	Direct current
DCRP	Direct current reverse polarity
DCSP	Direct current straight polarity
DOF	Degree of freedom
DT	A trademark of Data Translation Co.
EWTh-2	American standard for tungsten electrode
Fe	Iron element
GMAW	Gas metal arc welding
GTA	Gas tungsten arc
GTAW	Gas tungsten arc welding
HAZ	Heat affected zone
He	Helium gas
IEEE	Institute of Electrical and Electronic Engineers
IN100	A nickel base alloy
IN718	A nickei base alloy
IUST	Iran University of Science and Technology
JWRI	Japanese Welding Research Institute

LIA	Laser Institute of America
LUT	Look-up table
Mb	Megabyte
Mn	Mangan element
NDT	Non-destructive testing
N.Y.	New York
PC	Personal computer
PID	Proportional, integrated, derivetive
RAM	Random access memory
RF	Radio frequency
RX-90	A six degrees of freedom robot
SAMPE	Society of Advanced Materials Processing Engineers
SPIE	Society of Photo Interpretive Engineers
TIG	Tungsten inert gas
TV	Television
UPM	Universiti Pertanian Malaysia

Abstract of thesis submitted to the Senate of Universiti Pertanian Malaysia in fulfillment of the requirements for the degree of Master of Science.

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September 1996

Chairman : Dr. Iskandar Baharin
Faculty : Engineering

A statistical-adaptive control method for weld bead penetration and joint following in Tungsten Inert Gas Welding as an approach to process control of robotic GTAW has been designed and the sections related to joint following and prediction of the bead width as well as penetration depth were simulated. Weld process parameters such as base current and time, pulse current and time, electrode tip to workpiece distance, filler traveling speed, torch speed and workpiece thickness were used for finding the equations which describe the interrelationship between the aforementioned variables and penetration depth as well as bead width. These equations were developed from the statistical regression analysis of 80 welds deposited using various combinations of welding parameters. For monitoring of workpiece thickness variations, an ultrasonic device was used.

In order to accurately control the weld trajectory, a CCD camera was used. The results showed that the misalignment of the progressive heat affected zone which is adjacent to the weld puddle can be detected and used for control of the weld trajectory. Also, it was found that scanning of a certain region of the captured image in front of the weld puddle decreases the data processing time drastically.

In continuation of this work, a cascade control system for control of welding velocity as well as an algorithm for off-line generation and control of weld 3-D trajectory was developed.

Abstrak tesis yang dikemukakan kepada Senat Universiti Pertanian Malaysia sebagai memenuhi syarat untuk Ijazah Master Sains.

KAWALAN SUAI BAGI PENUSUKAN KIMPALAN DAN
TRAJEKTORI UNTUK ROBOT GTAW

Oleh

BAHRAM H. MIR SADEGHI

September 1996

Pengerusi . Dr. Iskandar Baharin
Fakulti : Kejuruteraan

Suatu kaedah kawalan statistik-suai untuk mengawal penyerapan kumai kimpalan dan ikutan sambungan di dalam Kimpalan Gas Lengai Tungsten sebagai suatu pendekatan kepada kawalan proses robot GTAW telah direka bentuk dan bahagian yang berkaitan dengan ikutan sambungan dan ramalan bagi lebar kumai dan kedalaman penyerapan telah disimulasi Parameter proses kimpalan seperti arus tapak dan masa, arus denyut dan masa, jarak di antara muncung elektrod dan bahan, kelajuan rod kimpalan, kelajuan sumpitan api kimpalan dan ketebalan benda kerja digunakan untuk mendapatkan persamaan-persamaan yang dapat menggambarkan kaitan di antara pembolehubah-pembolehubah yang telah disebutkan tadi dengan kedalaman penyerapan dan lebar kumai Persamaan-persamaan ini dirumuskan daripada analisis regresi statistik terhadap 80 mendapan kumai dengan menggunakan berbagai kombinasi parameter kimpalan Suatu peranti ultrasonik digunakan untuk mengawasi perubahan ketebalan benda kerja

Kamera CCD digunakan supaya pengawalan terhadap lebar kumai kimpalan dan ikutan sambungan adalah tepat. Keputusan mendapati ketidaksejajaran perkembangan Zon Kesan Haba (HAZ) yang bersebelahan dengan kawah lakur dapat dikesan dan boleh digunakan untuk kawalan trajektori. Penelitian terhadap sebahagian kawasan imej tangkapan kamera di hadapan kawah lakur dapat mengurangkan masa pemprosesan data secara mendadak.

Sebagai lanjutan untuk kerja ini, satu sistem kawalan lata bagi pengawalan halaju keluaran kimpalan dan cara bagi penjanaan dan kawalan luar-talian untuk trajektori kimpalan 3-D telah dibangunkan.

CHAPTER I

INTRODUCTION

Scope of the Problem

The main problem in robotic welding is the control of the welding process itself Basically robotic welding systems do not incorporate the adaptive skill of a human welder In manual welding, the welder adjusts the welding parameters according to what he 'sees' An alternative solution is to make the robotic welding system to adjust itself to the changing environment This is in contrast to pre-programmed welding robots which are taught to perform exclusively in a pre-defined path with iterative tasks The most challenging area in this relation is the research and development of a comprehensive and multi-purpose real-time sensing or control system for robotic welding

Previous works on control of penetration depth by considering the thickness of specimen can be grouped into two principal categories firstly, study on maintaining a fixed penetration depth in plates /sheets with constant thickness (Banerjee *et al* , 1992, Street, 1985, Zhang, 1992) and secondly, a more difficult one, maintaining a fixed penetration depth in plates /sheets with varying thickness (Nagarajan *et al*, 1989) In relation to adaptive control of joint following, several methods such as through-the-arc sensing (Cook, 1983, Hughes, 1985), vision systems (Richardson *et al*, 1983, Inoue *et al*, 1980, Arata *et al*, 1973), projecting and scanning laser techniques (Nayan and Ray, 1990, Smati *et al*, 1984, Corby, 1984, Morgan *et al*, 1983), ultrasonic sensing (Fenn, 1985), magnetic field sensing (Gerhard, 1991, Goldberg, 1985) and infrared thermography (Nagarajan *et al*, 1989, Chin *et al*, 1983) have been used and reported

The present work describes an effort to independently control welding process by on-line monitoring of changing work-piece thickness and progressive HAZ as well as off-line control and planning of weld trajectory The method proposed is new

Although no general mathematical solution for the automatic control of any possible sophisticated welding tasks exist, one approach is to select the most appropriate solution from an existing system by some kind of decision module from the welding task planner data base It means that for different welding machine, related control equation will be selected

Robot vs Human

The word '*robot*' originates from the Czech word '*robota*' which means '*slave*' The word '*Robotics*' was used for the first time by Isaac Azimov (Paul, 1979), on the basis of his three famous rules of robotics The most accepted definition for a robot is by RIA (Robotic Industries Association) which defined : a robot is a reprogrammable, multifunctional manipulator designed to handle materials, parts, tools or special devices through variable programmed motions for the performance of a variety of tasks (Malcom, 1988).

Eversince robots were introduced to society, people had always asked about their applications, reliabilities and economic benefits. Some benefits of using welding robots are: removing human operator from harsh and dangerous work environment, doing repetitive, lengthy and prolix tasks with high accuracy, and that is to four times faster than a human welder (Mckerrow, 1991).

Robotic Welding at a Glance

One major application area for industrial robots is welding. The use of welding robots was mainly pushed by the need for high quality welds in shorter cycle times and better environmental conditions.

Compared to manual welding, a robot welding system has no time limit even though with intense heat or thermal radiation conditions originating from the arc of the torch. In fact, manipulation of the torch for high speed welding, is not physically feasible with manual welding techniques as compared to robot welding.

A study of robots in the welding industries has shown an increase towards the utilization of more robots in a more complex welding industries. The areas most applicable for robotic welding are in the automotive, aerospace, military, nuclear and process industries.

Desired Features of an Arc Welding Robot

An industrial arc welding robot must have certain features and capabilities as follows:

1- Precision of motion and velocity.

2- 6 DOF.

3- Resistance to RF noise originated from arc.

4- Enough work envelope for the different part sizes.

5- Resistance to severe thermal radiation, spatter and smoke.

Benefits of Arc Welding Robot Utilization

Arc welding robots can provide a number of benefits compared to manual operation, such as:

1- Higher quality welds.

2- Material cost reduction (by reducing the number of scraps).

3- Increase of productivity.

4- Rationalization of the welding process.

5- Safety improvement by removing the operator from the hazardous and harsh environment.

6- Performing of difficult welding operations like overhead welding.

7- Higher weld consistency.

Flexible Welding System Concepts

The design, build and installation of flexible welding systems need high capital expenditure. Prior to this, all factors which can greatly affect the successful installation and implementation of the system should be carefully studied and investigated. It is recommended that before installation and operation of a robotic flexible welding system, a complete feasibility study is performed.

A flexible welding system includes several flexible welding cells in such a way that simultaneous manual or automatic work is possible on different workpieces. This characteristic enables the system to perform multi-product manufacturing in a single flexible automated system (Vettin, 1982).

The flexible welding cell includes one or more welder robots operating at a single welding workplace with at least one workstation and spatially separate manual or automatic loading/unloading. Station change is automatic, but workpiece change can be manual or automatic (Vettin, 1982).

Finally, a flexible welding transfer line includes flexible welding cells and, if necessary, further automated workstations for cutting and so on, can be linked by an automated material flow system. This line is capable of simultaneous or sequential processing of different workpieces, which pass through the system along the same path (Vettin, 1982).

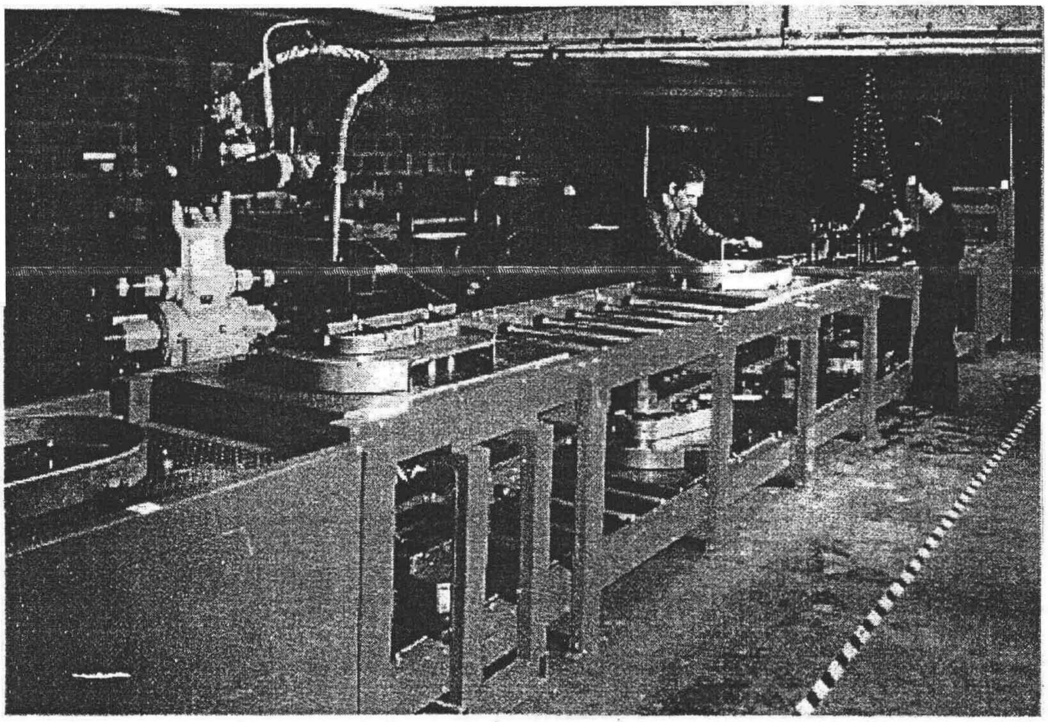

Plate 1: A Flexible Welding Transfer Line (Mckerrow, 1991)

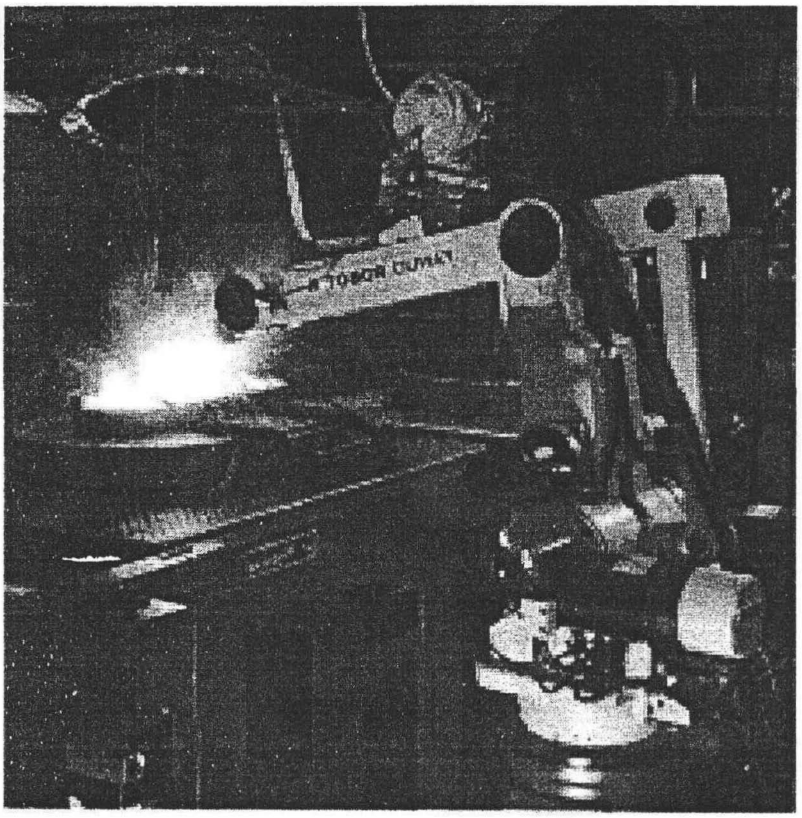

Plate 2: A FANUC Industrial Robot is Performing Welding on a Part which is Locked into the Pallet in Transfer Line (Mckerrow, 1991)

Plates 1 and 2 show two examples of a flexible welding system and transfer line.

Objectives

The research work was carried out in four stages as follows:

1. Developing of a statistical adaptive model for control of weld penetration by considering workpiece thickness.

2. Developing of the algorithms for joint following and processing of data through a region limited of captured images.

3. Developing of a control model for the control of the statistical-based welding equation.

4. Developing of an off-line planning and control algorithm for 3-D weld trajectories.

Organization of the Thesis

The next chapter gives a survey on previous works related to this thesis. Four main topics in this chapter are discussed: vision system, heat affected zone, penetration depth control, and joint following.

Chapter III gives a theoritical background on some of the main concepts used in this research.

Chapter IV indicates the apparatus and methods developed for the present work.

Chapter V describes the results obtained based on the experimental simulation work. The results of this research are divided into two sections. The first section gives an experimental model for adaptive control of penetration depth. The importance of this model is that, for the first time the thickness of workpiece has been integrated to the other welding parameters for control of weld penetration. This case increases the flexibility of the robotic welding with respect to the welding of the different parts with varying thickness. The second section introduces a method for the control of joint following through the thermal affected region around the weld fusion zone. Also, a method for a very fast processing of image data or ultrareal-time processing that can be utilized for decision making in the joint following stage, is proposed. This chapter gives a discussion on the results obtained and details some implementation problems as well as outstanding features of the results. Additionally, it gives some advice for the future work in this direction.

Chapter VI deals with the solving of welding velocity control based on the speed equation developed in Chapter V. A simulation work on the control system evolved is done to show the validity of it.

In Chapter VII, a combination of weld penetration and trajectory control is discussed, while a method for off-line weld 3-D trajectory generation is introduced. A simulation work for visualizing and validating the concept is presented.

Finally Chapter VIII summarizes and concludes the research work by exhibiting the main contributions of this investigation.