

利用“半径—深度”算法和空间投影关系的焊缝定位方法

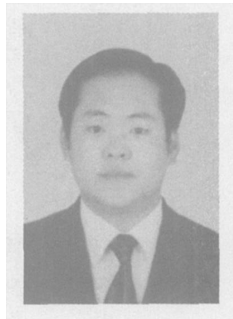
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摘 要: 提出了三个重要的角度来描述被测焊缝三维信息。在此基础上, 构建了基于“半径—深度”算法和空间投影关系的深度恢复模型。研究了 GTAW 焊接条件下焊缝深度信息与离轴角之间的关系。并对焊缝特征点进行了识别与定位。并用均方误差 (MSE) 对恢复精度进行了比较。结果表明, 利用提出的深度恢复算法, 实现了对接焊缝与斜坡焊缝的深度恢复, 获得了满意的结果; 视觉传感器的焊缝定位精度具有高效率、高精度的特征, 具有较理想的发展前景。

关键词: 激光锥体投影; 环形激光轨迹; 深度恢复; 焊缝定位

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0 序 言

为了实现焊接自动化, 实时自动地获得焊缝的定位信息, 已经开发了许多传感技术。其中, 视觉传感器由于其非接触、反应快速、抗干扰能力强而受到广泛关注。焊接熔池的自动控制通常采用被动视觉传感方法, 因为主动光技术由于熔池强光的干扰而无法进行^[1]。目前的研究中, 主动光传感技术所利用的检测激光轨迹包括^[2~6]: 点状激光、单条状激光、双线条激光、五线条激光或环形激光。但是点状或线条状激光视觉传感器信息量少; 存在解释模糊; 跟踪精度差及仅能一维或二维方向焊缝定位跟踪等问题。利用线阵 CCD 作为接受器的环形激光视觉传感器由于同样采用三角测量方法, 要求结构符合 Scheimpflug 条件^[7~8], 除了采用主动或被动视觉技术外, Rapha L^[9] 结合主动视觉和被动视觉的优点, 开发了基于立体视觉和激光扫描器多障碍物的自动识别系统。

结合环形激光视觉传感思想与面阵 CCD 的优点, 开发了一种新型的视觉传感器, 基于环形激光与面阵 CCD 视觉传感器的优点是: 可以进行焊缝三维检测, 精确计算焊缝特征点 3D 坐标, 实现焊缝三维的同时跟踪; 基于焊缝环形激光三维测量序列图像, 可以预知焊缝变化趋势; 可用于工件边缘快速搜索、

准确定位, 不受工件形状影响。提出了差分算法和模板方法来识别焊接接头的特征点, 并利用摄像机成像规律和“半径—深度关系”算法, 建立了焊缝特征点的三维模型, 以对接焊缝与斜坡焊缝为例进行了试验验证。

1 焊缝 3D 计算视觉模型

在视觉传感器中, 提出了三个重要的角度, 扫描锥角 α , 分离角 β 与离轴角 γ 。其中扫描锥角 α 是旋转透镜的扫描过程中的最大角度, 是光学系统中的重要参数, 由环形激光的扫描规律决定, 包括需要获得的环形激光的半径大小以及取样高度等。分离角 β 是 CCD 摄像机主光轴偏离激光二极管轴线的角度, 直接决定采集图像的质量和环形激光轨迹在像素平面坐标系中的椭圆度。目前, 还没有成熟的理论来指导 β 角的选取。 γ 角的范围为 $\gamma \in [0^\circ \sim 360^\circ]$, 该角度的定义是为了解决像素坐标系检测点的排序问题, 决定着每个检测点成像规律。

环形激光检测轨迹是通过扫描机构旋转形成^[10], 为了获得被焊工件的三维信息, 环形激光轨迹的成像过程被分为两个阶段: 一个是激光从激光二极管发射、经旋转扫描系统旋转成环形激光轨迹并投射到被焊工件上, 另一个阶段为环形激光轨迹在被焊工件表面漫反射在面阵 CCD 摄像机中的成像过程。环形激光投射到工件及其在摄像机中的成像模型如图 1 所示。模型构建过程的原则是将所有

点坐标、直线方程经过坐标系变换关系转换到激光锥体坐标系下。

构建如下

$$(x-r)^2+y^2=r^2。(3)$$

该方程也是激光投射模型中锥体方程的一部分,属于锥体曲线方程。

所以当 $x_L \neq 0$ 时

$$r=\frac{x_L^2+y_L^2}{2x_L}。(4)$$

根据环形激光设计原理及激光锥体投射规律,试验中任一半径 r , 该点深度 z_L 与传感器设计半径 r_0 之间的关系可由下式表示,即

$$\frac{r}{r_0}=\frac{175-z_L}{175}。(5)$$

即

$$z_L=\frac{175(r_0-r)}{r_0}。(6)$$

另一方面,当 $x_L=0$, 检测点深度利用激光三角测量原理来计算,其模型为

$$z_L=\frac{(l'-f)\cdot\Delta}{f\cdot\sin\beta+|\Delta|\cdot\cos\beta},(7)$$

式中: f 是镜头焦距; Δ 是激光像点在摄像坐标系中沿 x 轴方向的移动距离。

2 焊缝 3D 计算与定位结果

利用环形激光视觉传感器和提出的深度恢复算法、计算对接 V 形坡口(60°)、对接间隙焊缝及斜坡焊缝的三维信息,探讨深度值 z_L 与离轴角 γ 之间的关系、焊缝 3D 模型。在深度恢复之前,需要精确标定两个重要角度,其中,扫描锥角 $\alpha=12^{\circ}53'$, 分离角 $\beta=39^{\circ}15'$ 。标定误差 $25'10''$ 。

2.1 深度值 z_L 与离轴角 γ 的关系

利用环形激光视觉传感器,在采集的一幅图像中,可以获得多个测量点的深度值。试验中,对接 V 形坡口测定了 580 个扫描点;对接间隙焊缝测定了 464 个扫描点;搭接接头测定了 486 个扫描点;角接头测定了 515 个扫描点;环形焊缝测定了 544 个扫描点;斜坡焊缝则可以实现 400 个扫描点的测量。对接焊缝的深度值 z_L 与离轴角 γ 之间的关系如图 2 所示。

从深度值 z_L 与离轴角 γ 之间的关系曲线可以看出,深度的最大偏差出现在 $\gamma=\pi$ 左右的位置。最大偏差值为 2.8 mm,原因可能由 x_L 的取值引起的。

2.2 焊缝 3D 计算结果

分别利用“点状激光”和环形激光作为主动光源,焊缝 3D 计算理论分别采用激光三角测量原理和提出的“半径—深度关系”算法,将激光投射到斜

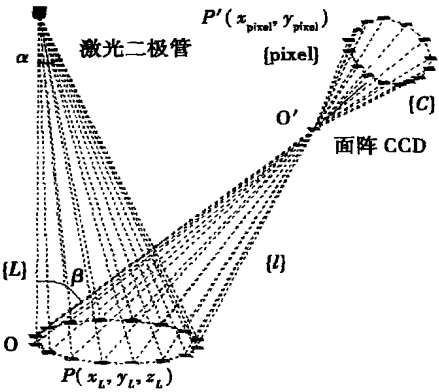


图 1 空间投影原理

Fig. 1 Projection model for 3D calculation

首先,从光线接收系统来考虑,设 $P(x_L, y_L, z_L)$ 为环形激光轨迹与工件的交点(即激光投射到工件上的点)在激光锥体坐标系中的坐标,其在像平面中的成像点在摄像机坐标系中的坐标为 $P'(x_{\text{pixel}}, y_{\text{pixel}})$, 根据空间投影关系与摄像机成像定律,像点在激光锥体坐标系中的坐标 $P'(x_L, y_L, z_L)$ 由下式计算,

$$\begin{cases} x_L'=-x_c\cdot\cos\beta+l'\sin\beta, \\ y_L'=-y_c, \\ z_L'=l'\cos\beta+x_c\sin\beta, \end{cases}(1)$$

式中: l 是激光锥体坐标系坐标原点与摄像机坐标系原点之间的距离。令 l' 是激光锥体坐标原点与摄像机镜头中心之间的距离;则镜头中心点在激光锥体坐标系中的坐标为 $O'(l'\sin\beta, 0, l'\cos\beta)$, 而且由于传感器总体相对位置不变,所以该点是恒定的。根据摄像机成像原理,在激光锥体坐标系下,物点 P , 像点 P' 和镜头中心 O' 必在同一条光线上,所有的这样的光线组合在一起的光线簇,就构成了环形激光的空间投影。因此,空间直线 PP' 属于经过 P' 点和 O' 点的直线簇 $\{l\}$ 。

$$\frac{x-l'\sin\beta}{m}=\frac{y}{n}=\frac{z-l'\cos\beta}{p},(2)$$

式中: m, n, p 分别是空间直线沿 x, y, z 三个方向的单位矢量。用矢量 $s=\{m, n, p\}$ 表示,由 P' 点和 O' 点坐标决定,很明显,物点 P 也属于上述方程并由该方程确定其坐标。

其次,考虑环形激光形成原理,根据激光旋转机构的设计模式,激光锥体坐标系中的每一个点都有唯一确定的半径与之一一对应。因此,激光锥体坐标系中任一点坐标 x_L, y_L, z_L 与半径 r 的关系方程

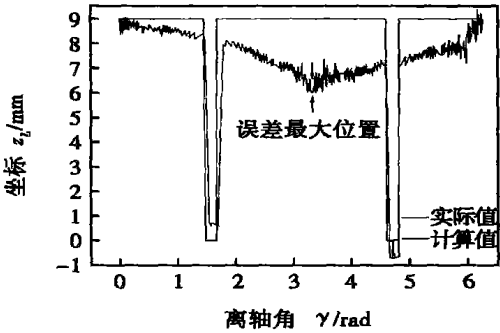
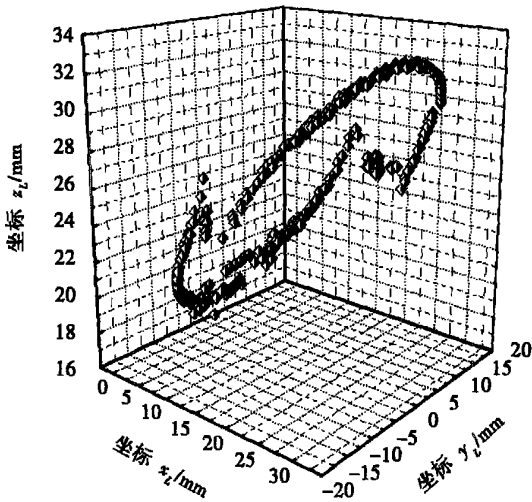
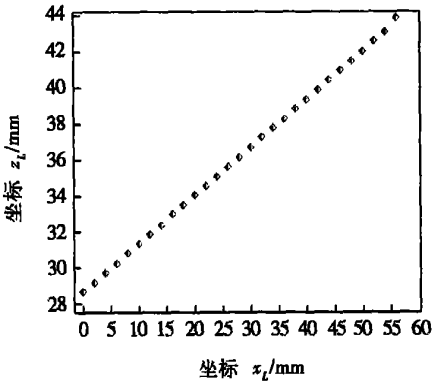


图2 深度 z_L 值与离轴角 γ 的关系
Fig. 2 Relation of depth value z_L and γ

坡焊缝上,对两种焊缝的 3D 计算进行研究。利用环形激光视觉传感器采集了一幅图像,斜坡焊缝则可以实现 400 个扫描点的测量。当采用“点状激光”作为主动光时,沿着 x 方向采集了 51 幅图像,采集间隔为 2 mm,这样可以恢复这 51 个位置的深度值,每一幅图像可以决定该点所在的焊缝 3D 值,结果如图 3 所示。



(a) 环形激光视觉传感技术



(b) 激光三角测量技术

图 3 斜坡焊缝 3D 计算结果

Fig. 3 Results of 3D calculation for ramp welded seam

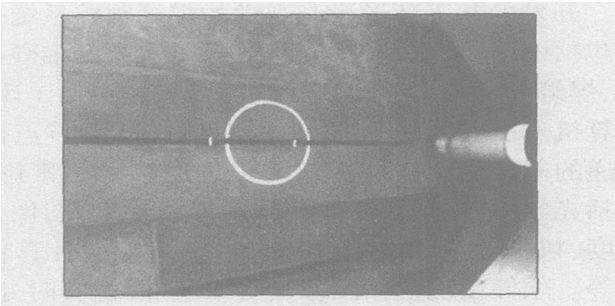
以深度为例,3D 恢复精度用 MSE 指标进行判定。 MSE 定义如下

$$MSE = \frac{1}{N_i} \sum_{i=1}^{N_i} [z(i) - z(i)']^2 / z(i)^2, \quad (8)$$

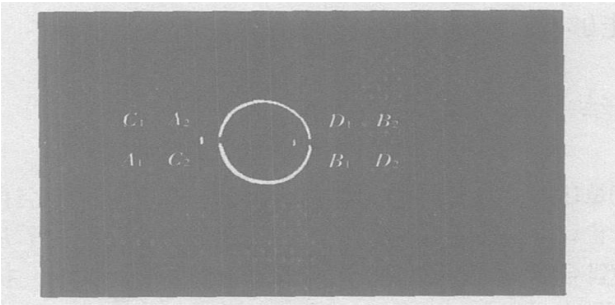
式中: $z(i)$ 是第 i 个位置的计算值; $z(i)'$ 是该点的实际值。结果表明,环形激光视觉传感方法 MSE 为 0.029 9,而“点状激光”的三角测量方法为 0.436 8。利用 NI1409 图像采集卡,在 PIII 主频 780 Hz 处理器、内存 384 M 的计算机工作环境以及 ABB—IRB1400 机器人 C/S 通讯方式下,一幅图像采集、分割、3D 计算总时间不超过 50 ms,能够满足 GTAW 焊接要求,比较而言,提出的环形激光视觉传感方法高效、高处理速度,这是面阵 CCD 摄像机的典型应用。

2.3 焊缝定位结果

利用模板技术搜寻焊缝特征点,以对接接头焊缝定位为例,图 4a 为视觉传感器采集到的对接接头原始图像,图 4b 为分割后图像及待测特征点,定位结果如表 1 所示。



(a) 原始图像



(b) 分割后图像

图 4 对接间隙接头焊缝定位图像

Fig. 4 Image for seam location of butt joint with gap

从表 1 中可以看出,对于 x_L 值恢复情况而言,计算值与实际值偏差不超过 0.3 mm,对于 y_L 而言,特征点 B_2 的计算值与实际值偏差较大,这可能是由于检测激光成像遮挡引起的。正因为考虑到了遮挡的问题,焊缝宽度的计算采用上表面的点来进行, A_2 点和 C_2 点确定的焊缝宽度为 3.94, B_2 点和 D_2 点确定的焊缝宽度为 3.94。检测结果与理论值 4 mm

表 1 焊缝定位结果
Table 1 Comparison of seam location results

焊缝特征点	3D 坐标(计算值)			3D 坐标(实际值)		
	x_L	y_L	z_L	x'_L	y'_L	z'_L
A_1	39.74	2.32	0.59	40.00	3.00	0.00
A_2	38.28	-1.16	8.13	38.00	-1.00	9.00
B_1	0.01	0.69	-0.69	0.00	2.00	0.00
B_2	0.11	-2.09	7.04	0.00	-2.00	9.00
C_1	39.85	-0.46	0.72	40.00	-1.00	0.00
C_2	38.15	2.78	7.97	38.00	3.00	9.00
D_1	0.05	-1.39	-0.64	0.00	-2.00	0.00
D_2	0.11	1.86	7.01	0.00	2.00	9.00

之间的偏差为 0.06 mm。对于 z_L 值来说,比 x_L , y_L 的偏差值都大,检测点的深度绝对误差分别为 0.59, 0.87, 0.69, 1.96, 0.72, 1.03, 0.64 和 1.99 mm。误差较大的原因是 z_L 的求解累计了 x_L 、 y_L 的误差以及所需常数的测量误差引起的。

开发的基于环形激光视觉的焊缝跟踪系统是一个包括图像采集卡、视觉传感器、机器人的多硬件结合,焊缝图像采集与图像阈值分割、焊缝 3D 计算、计算机—机器人通讯多任务数据处理,多节点信息传递的复杂系统。焊缝跟踪精度受多种因素影响,包括光学扫描系统精度,摄像机标定精度、图像处理精度、机器人标定精度以及焊缝 3D 模型计算精度等等。软件系统包括图像实时采集、图像实时处理、三维计算、数据传递与基于 C/S 的机器人通讯等模块,能够满足实时跟踪的要求。

4 结 论

提出了基于环形激光轨迹焊缝定位的空间构架和三维计算模型。通过一系列的试验验证了所构建的模型合理,符合各种焊接接头定位要求。提出的模型具有高效、快速及精确的特点,基于标准 C++ 的加速算法更使其能够满足实时处理的要求。

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welding of aluminum alloy. The experiment results demonstrate that the addition of the metal powder enhances the energy coupling efficiency and reduces the power density threshold value during laser deep welding. Such as the reducing rate is about 50% for A2219 alloy. The experiment results also indicate that the powder can enter the weld pool available only the powder was delivered to the suitable area after laser beam at the surface of a part. The proper quantity of the alloy powder must match with the right power density and energy input, which can assure to obtain good weld appearance. Meanwhile, the addition of the powder can reduce the fluctuation of the laser-induced plasma and maintain its stability effectively in the laser welding. So a stable welding process and good weld appearance can be obtained in the experiments.

Key words: aluminum alloy; metal powder; CO₂ laser welding; laser induced plasma; power density threshold value

Effect of side gas on laser induced plasma during laser deep penetration welding ZHANG Lin-jie¹, ZHANG Jian-xun¹, DU-AN Ai-qin² (1. State Key Laboratory of Mechanical Behavior for Materials, Xi'an Jiaotong University, Xi'an 710049, China; 2. Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China). p37—40

Abstract: A two dimensional compressible gas flow model of laser penetration welding process was founded for a better understanding of the influence of side gas flow conditions on the behavior of laser induced plasma. The distributions of temperature and velocity within plasma plume under different side gas flow conditions were calculated. The shape and size of plasma in laser welding process was studied with high-speed CCD camera. The result shows that laser induced plasma and weld geometry are sensitive to side nozzle height, its inclination angle and side gas flow rate; that cooling effect and assist gas/plasma-plume momentum ration play an important role in controlling the plasma plume.

Key words: laser deep penetration welding; side assist gas; numerical simulation; high-speed CCD imaging

Mechanical properties and microstructures of QFP micro-joints soldered with diode-laser soldering system HAN Zong-jie, XUE Song-bai, WANG Jian-xin, CHEN Xu (College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China). p41—44

Abstract: Soldering experiments of two kinds of devices QFP32 and QFP48 were carried out using diode-laser soldering system and IR reflow soldering method, and the distribution regulations of the tensile strength of QFP micro-joints with Sn-Pb solder and Sn-Ag-Cu lead-free solder were studied by STR-1000 micro-joints tester, and the characteristics of fracture microstructures of micro-joints were also analyzed by SEM. The results indicate that tensile strength of QFP micro-joints soldered with laser soldering system is larger than that with IR reflow soldering method and tensile strength of QFP48 micro-joints is larger than that of QFP32 micro-joints. Fracture mechanism of micro-joints soldered with laser soldering system is toughness fracture, while fracture mechanism of micro-joints soldered with IR

reflow soldering method includes brittle fracture and toughness fracture.

Key words: diode-laser soldering; QFP devices; mechanical properties of micro-joints; microstructures

Active vision sensing method for weld location by "circle-depth relation" algorithm XU Pei-quan, TANG Xin-hua, LU Jian-bo, Yao Shun (School of Material Science and Engineering, Shanghai Jiaotong University, Shanghai 200030, China). p45—48

Abstract: Three vital angles were put forward, so the weld could be described by three-dimensional information. On this basis, mathematical model of depth recovery according to "circle-depth relation" algorithm and projection rules was constructed. The relationship between depth values and off-axis angle γ under gas tungsten arc welding experiment condition was addressed by real experiment and the characteristic points of weld was described and located. Mean square error was used to analyze the recovery precision. The results showed: (1) Depth recovery for butt joint and ramp welded seams realized; (2) Weld can be located very well by using proposed vision sensor based on circular laser trajectory; and proposed vision sensor manifested a promising result with high precision and high efficiency.

Key words: laser cone projection; circular laser trajectory; depth recovery; seam location

Instantaneous energy waveform of short circuiting transition in CO₂ arc welding XUE Jia-xiang, YANG Guo-hua, WANG Zhen-min, LIU Xiao, HONG Sen (College of Mechanical Engineering, South China University of Technology, Guangzhou 510640, China). p49—52, 84

Abstract: The welding process of three arc welding machines had been tested and analyzed with the welding dynamic arc wavelet analyzer developed by the authors. The experimental results indicate that the instantaneous energy can synthetically reflect the influence of current and voltage on dynamic arc characteristics. To make arc ignite successfully, the instantaneous energy should increase to enough high quickly along with the current. In a cycle of short circuiting transition during the steady welding process, the instantaneous energy during arc burning should be kept at the constant base, and then it falls to smaller value rapidly, finally, it rises rapidly and completes the short circuit transition. The instantaneous energy falls again rapidly to base after arc re-striking. While arc extinguishing, the instantaneous energy falls slowly to zero and avoids serious impulsion. The experiment results can provide for the foundation to design and control accurately the waveform of the welding current and voltage.

Key words: instantaneous energy; wavelet analysis; repeatability of waveform

Effects of temperature and coatings on wettability of Sn-Cu-Ni lead-free solder WANG Jian-xin¹, XUE Song-bai¹, HAN Zong-jie¹, WANG Ning¹, YU Sheng-lin² (1. College of Materials Science and Technology, Nanjing University of Aeronautics and Astro-