Real-Time Implementation of a Joint Tracking System in Robotic Laser Welding Based on Optical Camera

Qi Zhang, Shanglei Yang, Haobo Liu, Chaojie Xie, Yaming Cao and Yuan Wang

Abstract Robotic laser welding has been widely applied to industries due to its high flexibility and productivity. However, there are still some constrain such as heat induced deformation and inevitable fixture errors, which can affect the laser beam positioning to deviate from joint center, and that will lead to poor welding quality. In order to ensure high quality welding, a joint tracking system is needed to track the joint center in real time to keep the focus of laser beam following the weld joint consistently. This paper introduces laser welding, describes composition of a real-time joint tracking system which mainly includes image acquisition part, image process and analysis part, and motion control part, reviews relevant investigations of joint tracking system and algorithm. Although there are successful applications in real-time joint tracking, the systems and algorithms can only be used in limited situations. So, future research can be focused on problems such as the promotion of system performance, the commercial solutions for joint tracking, etc.

Keywords Laser welding · Robotic welding · Real-time · Joint tracking

1 Introduction

1.1 Problem Description

Compared with manual welding which is time consuming and inefficient, robotic welding has high flexibility and automation. At the same time, laser welding can realize deep penetration and improve mechanical properties due to a narrow heat

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affected zone compared with other welding techniques e.g. arc welding [1, 2]. So, there would be more application space for robotic laser welding considering advantages of both robotic welding and laser welding.

However, there is only limited success in many welding applications because of many robotic laser welding systems can't adapt to real-time changes of joint or environment such as thermal distortion from the intense heart of the laser beam, fixture errors or improper preparation of the weld joint [3, 4]. These variations will lead to laser beam wandering off the joint and result in bad quality e.g. lack of penetration, unacceptable welds, and reducing of heat efficiency largely [5, 6], such as Fig. 1. Thus, in order to compensating these variations in changeable environment in real time and getting good welding quality, joint tracking is needed to keep laser beam following the weld joint in real-time consistently.

1.2 Related Work

There have been many investigations about real-time joint tracking. Reference [3] proposed a method for seam-tracking which was based on infrared sensors, the molten pool infrared images are got through camera at first, then, thermal distribution of joint is analyzed, finally, a dynamic visual model which can measure the offset between laser-beam focus and weld-seam center was established. A laser welding experimental platform for burred joint welding is introduced in [7], they proposed a novel vision sensor system, images of burred joint can be acquired accurately based on their system and the final quality of welding is good. Reference [8] proposed an automatic seam tracking system which used for multi-pass arc welding, and an algorithm which used for image processing was also proposed. The results showed that the system and algorithm have good performance for image processing and seam tracking. Reference [9] proposed an algorithm for real time

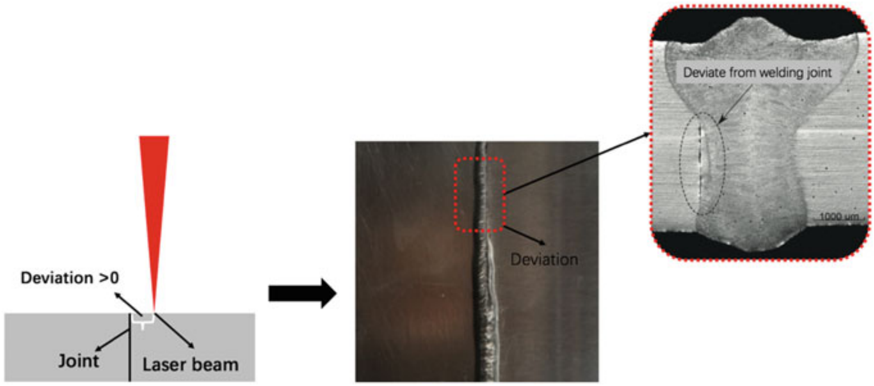


Fig. 1 Deviation between laser beam port and joint center leads to poor quality

seam detection and feature extraction, the algorithm they proposed has good stability and accuracy. There are also welding applications in actual production. The joint tracking system that based on laser is used for multi-pass welding of thick wall in [10] and there are high production quality and production efficiency. In [11], the joint tracking system which named Smart Laser Probe and made by Meta company is used for production line of continuous welding of stainless steel.

Although there have been a lot of researches and improvements in real-time joint tracking, these systems and algorithms are used for specific situations usually and cannot be used directly in other situations, research and innovation are still needed to focus on such as optimization of the algorithms, robust and efficiency of the system.

2 Laser Welding

Laser welding is an efficient and precise welding method which using high energy density laser beam as heat source, see Fig. 2. It can realize deep penetration and narrow welds with less heat induced deformation under higher speed compared with other welding techniques e.g. spot welding [12]. It is widely used in many research areas e.g. aerospace industry, automotive industry, medical industry, etc.

The optical path and process of laser welding are shown in Fig. 2. At first, laser beams are generated in laser; then, laser beams are focused on work piece through optical focusing and pointing system which contains lens and mirrors; finally, the work piece can be welded together when the temperature reaches the melting point of the materials [13, 14].

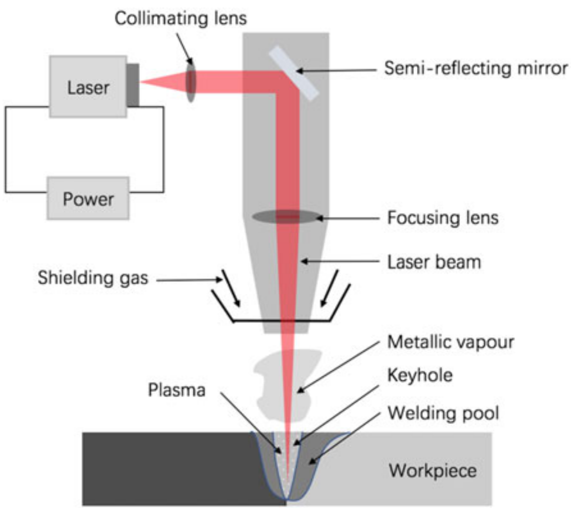


Fig. 2 Optical path and process of laser welding

Laser welding can be clarified into heat conduction laser welding and deep penetration laser welding according to the characteristics of formation of weld joint during laser welding [12]. The welding pool of heat conduction laser welding is wide but shallow. The laser power density of heat conduction welding mode is generally in 10^4–10^5 W/cm^2, a large part of laser is reflected by the metal surface which means the light absorption rate is low. The weld depth of heat conduction model is shallow and speed is slow, it is mainly used for welding of thin work piece (thickness <1 mm) [12]. Different with heat conduction welding, deep penetration laser welding has higher power density (10^6–10^7 W/cm^2). The magnitude of the power density can cause melting and vaporization of metal materials rapidly, and a keyhole is formed in the laser irradiation point. The keyhole continues to absorb light energy and the welding pool is formed, heat diffuses to around through the welding pool. The welding pool can be affected by laser power, the larger the laser power, the deeper the welding pool will be.

3 The Real-Time Joint Tracking System

3.1 *Description of a Real-Time Joint Tracking System*

Joint tracking which can be seen as a form of visual serving usually focus on control-loop of sensors which focus on image acquisition, algorithms which focus on image processing, and manipulators which carry out the motion commands [15]. The composition of joint tracking system is almost the same between laser welding and other welding methods, the biggest difference is information acquisition and processing, which due to different features between different welding methods.

There is the overview of the process of a close-loop control for joint tracking, see Fig. 3. Real-time joint tracking system usually contains three parts: image acquisition part which aims to obtain the joint information usually based on cameras or other types of sensors; image processing part which focus on processing images and making decision usually based on industry computers; motion control part which carries out the commands made by computer usually includes manipulators and laser device [6].

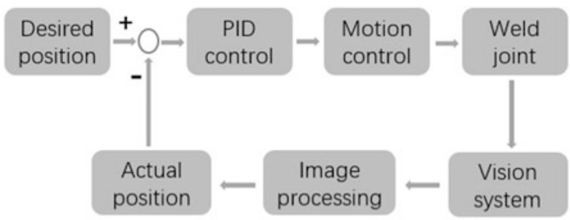


Fig. 3 Principle of the close-loop control for joint tracking

Coordinate frame

Coordinate frame is an important part that need to be considered for real-time joint tracking system. There are several coordinate frames for real-time joint tracking system: robot base coordinate frame; TCP (Tool Centre Point) coordinate frame; camera coordinate frame and work piece coordinate frame [6, 17]. In order to obtaining trajectory of robot, transformation between different coordinates is needed. Figure 4 shows frames of sensor-guided robotic laser welding.

Transformation from image plane to work piece coordinate which represents real world is needed to convert a spatial point from 2D coordinate to 3D coordinate, see Fig. 5. It can be determined by following homogenous matrix:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = Q \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{1}$$

As Fig. 5 shows, X, Y, Z represent coordinate of points in workpiece frame while u, v represent coordinate of the same points in image plane. Q is a transformation matrix, which is influenced by intrinsic and extrinsic parameters of camera, can be calculated by following matrixes:

$$K = \begin{bmatrix} \alpha_x & s & u_0 \\ 0 & \alpha_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} [R \quad T] \tag{2}$$

K is matrix of intrinsic parameters of camera, which can be acquired though camera calibration. [*R T*] is matrix of extrinsic parameters, *R* is a rotation matrix

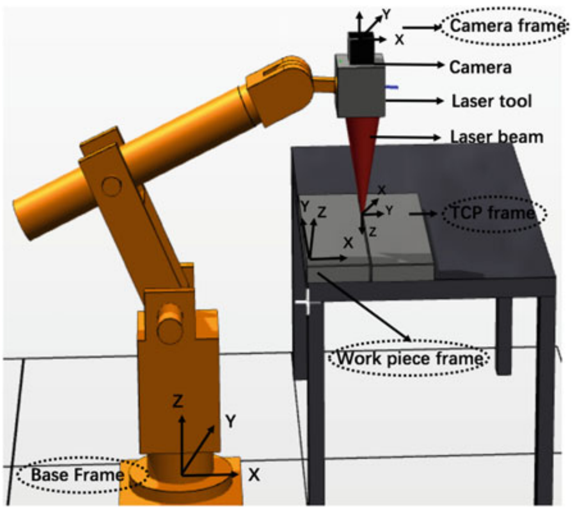


Fig. 4 Frames of sensor-guided robotic laser welding

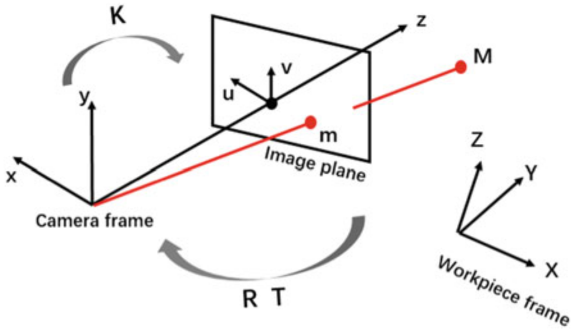


Fig. 5 Transformation from image to real world

while T is a translation matrix. Points in real word can be translated into image plane according to these matrixes [6, 16].

Transformation from TCP frame to work piece frame is needed, which describes the position and orientation of TCP coordinate system with respect to work piece coordinate [6, 17]. This can be accomplished through kinematic modelling [6]. The homogenous transformation matrix can be expressed as below:

$$ {}_{A}^{W}T = \begin{bmatrix} {}_{A}^{W}R & {}_{A}^{W}P \\ 0 & 0 \end{bmatrix} \tag{3}$$

where A represents the coordinate of TCP while W represents the coordinate of work piece. ${}_{A}^{W}T$ is a 3×3 matrix which means transformation from TCP frame to work piece frame. ${}_{A}^{W}R$ is a 3×3 rotation matrix, which represents rotation relationship from TCP coordinate to work piece coordinate; ${}_{A}^{W}P$ is a 3×1 transfer matrix, which represents position vector that describe the position of TCP frame relative to work piece frame.

Manipulator Kinematics

Kinematics, which contains forward kinematics and inverse kinematics, is very important for a joint tracking system. Forward kinematics aims to ensure the position and orientation of end-effector according to relationship between different joints and coordinates while inverse kinematics aims to calculate the change of every joint according to the known position and orientation of end-effector and transformation between different coordinates. It determines whether the end-effector can reach the right position correctly [6]. This relates to the coordinates relationship between TCP, camera, and work piece. There are mathematic models can be used to calculate the forward and inverse kinematic relationship of joint tracking system, such as [17] built the full kinematics model of mobile welding robot by using D-H (Denavit-Hartenberg) homogeneous transformation method which is used for establishment of coordinate of every joint and link of robot.

In order to establishing the kinematic model of robot, D-H rules should be followed to establish coordinates at first. Then D-H parameters of every joint and link of robot should be measured and calculated [16, 17]. Transfer matrix that based on D-H can be expressed as follows:

$$T = \begin{bmatrix} C\theta_i & -S\theta_i & 0 & 0 \\ S\theta_i & C\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & l_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C\alpha_i & -S\alpha_i & 0 \\ 0 & S\alpha_i & C\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

$$T = \begin{bmatrix} C\theta_i & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & l_i C\theta_i \\ S\theta_i & C\theta_i C\alpha_i & -C\theta_i S\alpha_i & l_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

$${}^0_6T = {}^0_1T\,{}^1_2T\,{}^2_3T\,{}^3_4T\,{}^4_5T\,{}^5_6T \tag{6}$$

$C\theta_i = \cos\theta_i$, $S\theta_i = \sin\theta_i$, $C\alpha_i = \cos\alpha_i$, and $S\alpha_i = \sin\alpha_i$. $[T]$ represents transfer matrix from the coordinate of one joint to another, $\left[{}^0_2T\right]$ represents the coordinate transfer from the second axis to robot base coordinate while $\left[{}^0_6T\right]$ means that the coordinate transfer from the sixth axis coordinate to robot base coordinate. Then, kinematic modelling can be established according to these equations and parameters. [17, 18]

3.2 Image Acquisition

It is very important to obtain high quality images in joint tracking system. The subsequent work will be meaningless if high quality images cannot be obtained. Acquisition of images usually influenced by e.g. the light source, the type of image sensor and disturbances like light emissions and vapour fumes during laser welding process [14].

CCD (Charge-coupled Device) and CMOS (Complementary Metal Oxide Semiconductor) are two common image sensors, which can convert optical signal into digital signal. They are both semiconductor devices, Fig. 6 shows a type of CMOS image sensor. Frame rate of camera sensor, which means frames that can be captured or transmitted per second, will influence time of image acquisition significantly, the higher the frame rate, the faster the image acquisition [13]. ROI, which means image area that selected to be acquired and processed, will affect frame rate of camera and time of image acquisition, decrease of ROI can increase frame rate and speed of image acquisition of camera sensor. ROI can be defined by users through different operators and functions.

Disturbances from laser welding process e.g. light emissions and vapour fumes will also affect image acquisition. Light emission, which mainly includes reflection

Fig. 6 A type of CMOS image sensor

of laser beam light, heat radiation of welding pool, and radiation of laser beam, is an inevitable influence factor for image acquisition during laser welding [13]. In general, the stronger the light emission, the more difficult the image acquisition. In [19] reflected laser light can indicate weld quality, it can be influenced by the deep of the keyhole, the deeper the keyhole, the less the reflected laser light. In [20] reflected laser light is almost constant under stable welding process and will fluctuate with the state of welding conditions. It can be controlled by suitable filter. Light emission is also influenced by surface of materials, the smoother and brighter the surface, the stronger the light emission, such as there are stronger light emission for aluminum alloy compared with steel during laser welding. Light emission can be monitored by a photodiode by measuring its reverse current which related to light intensity. There is also research about vapour fume e.g. the vapour fume in CO_2 laser beam welding is monitored by a high-speed camera in [21]. As Fig. 2 shows, metallic vapour fume will be generated and diffuse over the weld joint during laser welding, metallic vapour fume that shield on weld joint is an interference for image sensor and will make image acquisition more difficult. It can be improved by different ways: e.g. extracting vapour fume by extraction system in real time; selecting suitable filter and putting in front of image sensor to reduce the influence of these disturbances.

In order to capturing images of joint in real-time, seamlessly and high-efficiency communication between camera and computer is need to be established through the interface standards which includes hardware standard and software standard [22]. Hardware interface standards aim to make sure that the hardware of vision system such as cameras, cables, and frame grabber can be connected well with each other while software standard aims to provide the same API (Application Programming Interface) for different cameras which have different hardware interfaces. There are two layers of software between camera and user application, see Fig. 7. The transport layer is the first layer which depends on the hardware interface, the main function of it is to access the camera and deliver streams. The second layer is image acquisition library which is governed by software interface standard.

Each camera has their own interface, such as the interface of CMOS camera in Fig. 6 is GigE Ethernet. SDK (Software Development Kit) which corresponds to interface of camera should be installed to build stream connection between camera

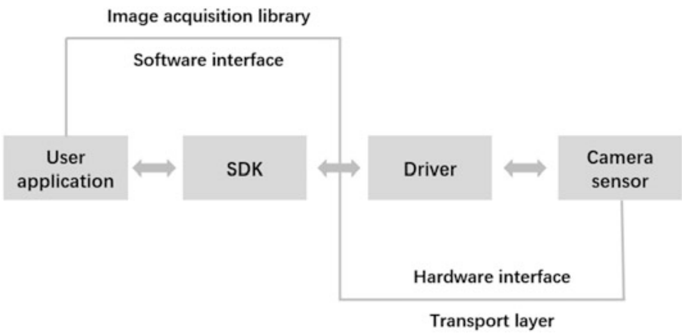


Fig. 7 Two layers of software between camera and user application

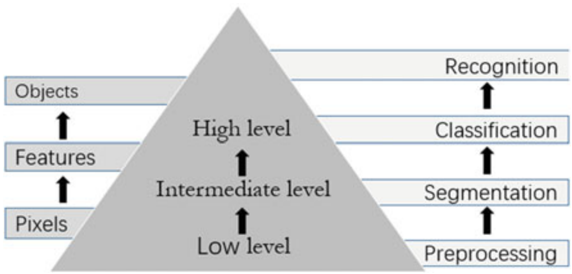
and user application through API (Application Programming Interface). In general, SDK can be found easily in Internet and there are enough programming samples which can be used directly.

3.3 Image Processing and Analysis

There is no doubt that the performance of joint tracking system will be decided by precision and speed of image processing. Image processing usually includes pre-processing, segmentation, classification, and recognition under different levels, see Fig. 8. It will be accomplished based on specific software and corresponding programming libraries and languages normally. Different programming libraries e.g. Open-CV and languages e.g. C++ can be used for image processing. Choosing of programming library and programming language should according to specific situation and requirements, because there is different performance e.g. speed or accuracy for different programming libraries and languages.

Algorithm is important for image processing and different algorithms can be used for different part of image processing. Such as in edge detection part of image processing, there are *Canny ()*, *Laplace ()*, *Sobel ()* and *Scharr ()* algorithms in Open-CV, there are different performance between them obviously, see Fig. 9.

Fig. 8 The general process of image processing



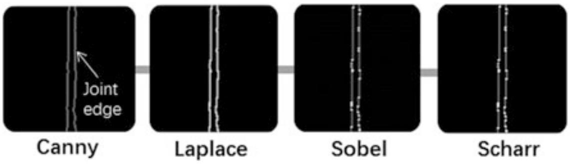


Fig. 9 Comparison of different algorithms for edge detection of image processing of butt joint

There have been many research about algorithms used for joint tracking. The modified Hough algorithm is used in [23] to process joint images, the results show that seam tracking can be accomplished in a shorter time in that paper. Reference [24] introduced a simple seam-tracking algorithm through characteristic-point detection using a laser-displacement sensor to detect the seam of single-butt welding with manually tack-welded non-zero gaps. Reference [25] used Kalman filtering algorithm to eliminate the influence of image noise and reduce error between the measurement position and real position of the objects. Improvement of the algorithms can promote the development of the welding, such as in threshold selection part of image processing for joint tracking, adaptive algorithm for thresholding is faster than manually selecting of threshold, which increases the react efficiency and improves the welding accuracy.

Algorithms are always the most important part for image processing, good algorithms should have higher precision and faster speed which may be the bottleneck of image processing. Although there have been many algorithms to use, these algorithms are not effective for all the conditions, so, these algorithms cannot be used directly usually. Improve, optimize and even create new algorithms according to the specific situation is needed.

3.4 Motion Control

After getting actual position of joint through image processing and analysis, decision should be made and sent to motion control part which includes control of robotic motion and welding parameters. Robot will receive signals from its controller and make corresponding compensation action, and then feedback the real-time position to computer in closed loop control system, see Fig. 3. The deviation should be compensated and get good welding quality in theory after implementation of motion control, see Fig. 10.

There has been much research about robot motion control system e.g. [14] proposed a trajectory-based control system which can generate trajectory of robot in real-time according to the data acquired from sensors. However, there is only limited success in practical industrial production. Externally guided motion (EGM), as a part of Robotware which is an ABB robot control software, can be used for robot motion control [26]. Tested accuracy and feasibility of EGM in laser welding application under different types of paths, results show that there is only minor influence which can be ignored in laser welding application.

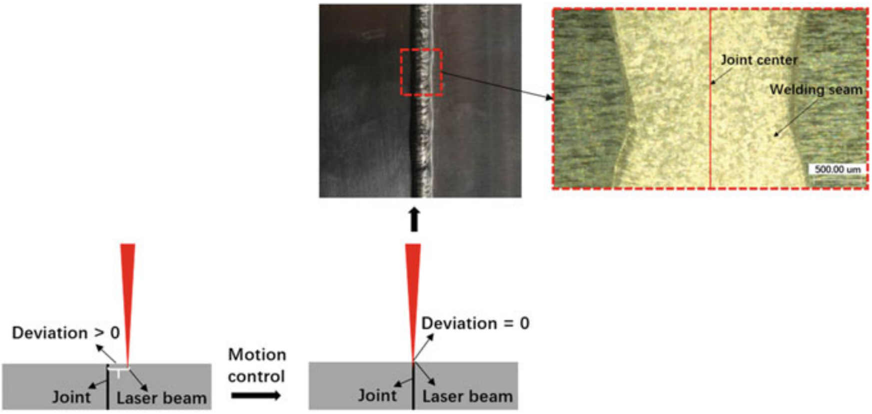


Fig. 10 Ideal motion control lead to zero deviation between laser beam port and joint center

In order to accomplishing motion control, mathematical model should be established to convert deviation signal got from image process and analysis part to signal of direction, distance or angle of robot joints in real time. The mathematical model can be built based on different software such as MATLAB.

4 Peroration

Considering limitations of robotic laser welding, which induces by real time changes in joint or environment, a real-time joint tracking system is needed to compensate real time changes and keep the laser beam following joint center consistently. In this paper, laser welding and composition of a real-time joint tracking system which mainly includes image acquisition part, image process and analysis part, and motion control part is introduced. Frames and kinematics modeling of joint tracking in robotic laser welding is also presented. Each part of joint tracking system can be influenced by different factors, such as image process and analysis part can be influenced by algorithms, programming library and programming language, etc. Communication between different part of joint tracking system can also influence the performance of the whole system through interface, API, etc.

Many relevant investigations of real-time joint tracking are reviewed in this paper, many systems and algorithms are proposed and successfully used for real-time joint tracking. However, these systems and algorithms can only be used in limited situations which mean specific applications, so, research and innovation are still needed to focus on improvement of robust and efficiency of the system, commercial solutions for joint tracking, etc.

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