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Advances in Visual Sensor based on laser structured light and its application for Robotic welding

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ABSTRACT

Currently, the technology of visual sensing based on laser structured light is used widely in industrial welding automation due to the many advantages of the laser structured light like non-contact with the workpiece, the ability of acquiring a lot of information with highest rate of precision, and the ease of extracting the image features. Therefore, many researchers started to use the visual sensor based on laser structured light because of the advantages of it. In this review paper, the recent studies and methods of visual sensors based on laser structured light have been reviewed. Moreover, the two types of detection methods for weld seam tracking have been discussed. These methods are passive vision and active vision. The increasing use of laser structured light as an additional light for obtaining accurate information about the welding seam tracking and the image feature extraction is because of the above-mentioned advantages of laser. In addition, this paper illustrates in detail the role of laser structured light in welding seam tracking and the merits & demerits of the laser-type. Moreover, the measurement methods of extracting the image features have been discussed. Thus, laser structured light has a very important role in weld seam tracking in making the system fully automated. Moreover, each one of laser structured light has disadvantages and disadvantages, depending on the application that is going to be used. This review paper presents the visual sensing with combination of the laser structured light, the mathematical modelling methods, the different types of algorithms for extracting the image features and the current challenges are highlighted in this review.

Key words: Active vision,Vision sensor, Laser structured light,Triangulation measurement.

I. INTRODUCTION

With advent of new technologies, welding manufacturing has been evolving to meet the industrial manufacturing demand where precision, real time, and efficiency are considered. The welding industries has transferred from original handwork craft to automated welding industries[1]. Automated welding industries came to increase the production, and save the time, which is can be achieved technically by developing the welding industries that automatically and dynamically able to sense and extract the information in welding process[2]–[13]**,** and recognize characteristics of welding process, and take action by controlling the process[14]–[22].

The employ of industrial welding robots in poor working conditions is crucial and essential where it helps to tackle many problems that's difficult to be handled by human being and some of the application that's be done by welding robots are Plants of nuclear power and ship building[23],[24].

There are two modes for welding robot operation which are teaching pendant mode, and offline programming mode. Both do not rely on the measurement of the sensor in the welding process. In addition, workers preset the welding trajectories in advance, so the movement of the robot will be set as it is desired. Therefore, these two types of modes are applicable only on static and coordinated welding system. In addition, these two modes are not robustness in complex and dynamic environment that usually the dimension will be changes[25]–[28].

Visual sensor has two categories which are passive and active vision methods. Active vision method use additional light that will be projected onto the workpiece and the acquiring of the image will be by CCD, whereas passive vision methods use ambient light to get the image of the welding area[29]**.**A lot ofresearcher have studied the application of active and passive vision and they compared the between them and found the image processing of active vision is simple, Arc interference is free from disturbance, information extraction is easy, and price is high.

Laser structured light use as auxiliary light and that is because of its advantages in the welding application. This review paper will discuss vision sensor based on laser structured light, the detection principle of visual sensor based on laser structured light, and Image processing and acquisition.

II. VISUAL SENSOR BASED ON LASER STRUCTRED LIGHT

Visual sensors have two types that use in manufacturing Welding which are based on structured light and based on scanning. The main difference between scanning and structured light mode is the scanning mode has a large and observable view of the world that can help to see a large field of view in the welding manufacturing. However, the detection accuracy is low and cannot be used in the application that demand high-precision detection. In addition, real-time performance of scanning mode is poor and cannot be used in the application that need a high control and high-speed weld seam tracking. Moreover, system structured of scanning mode is complex and it is mainly used for the guided positioning of robots [30]-[31].

Laser vision sensor has many characteristics and these characteristics depend on the types of laser structured light and also the numbering of the cameras that can be utilized[30]. There are many types of structured light which are dot, single line, multi-line, cross-line, grid, and coding structured light. In this paper, the single-line, cross line, and multi-line laser will be focused since these three types of structured light are most used in the welding manufacturing, because of their characteristics. Table 1 below is a comparison between the type of structured light[31].

Table 1:Comparison Between the Type of Structured Light

category	**Single-line structured light**	**Crossline structured light**	**multi-line structured light**
Image processing	relatively simple	Complex	Complex
Arc interference	Free from noise	Free from noise	Free from noise
cost	cheap	expensive	expensive
Feature extraction	Easy, but needs recalibration when its space posture or height changes.	welding groove can be realized directly	Easy and it has a great coverage area
application	(Vision industry, Laboratory applications, Medicine, Engineering, Automotive industry)	the weld seam tracking, industry, Laboratory, Engineering, Automotive	Vision industry, Laboratory applications, Medicine, Engineering, Automotive industry)
Advantages	The system and image processing are easy.	the realization of the welding groove can be tracked easily by finding theintersection point of the laser lines.	the ability to get more detection information and it can cover a great area
disadvantages	requires recalibration when there is change	The complexity of the system andperformance is poor	complexity of calibration &the image processing is difficult

Single line laser was used for identifying the ort and type weldingseam and get the location of the features[32] and to extract the image features like width, depth,the mismatch of the plates, and cross-sectional area[33].

Shao et al. [34] used three laser stripes for butt joint measurement with no misalignment and width less than 0.1 mm. The laser stripes have different wavelength, two of them are red to get 3-D profile of the weldment, and third green laser use to get the edge measurements as shown in Figure1. In addition, Zou et al. [35]also used three-wire laser generator for seam tracking system. Moreover, using three-line laser to get deviation measurement and identify the type of cross weld was done by Zhang[36], and to get 3D coordinate values of the weld feature points[37]. However, Guoliang Ye used laser line scanner to get the 3D bead measurement[38]. Junfeng Fan utilized laser emitter to fulfill seam tracking of narrow butt in the vertical and horizontal direction simultaneously as shown in Figure2[39]. Three-wire laser transmitter used for automatic seam detection and to get the Characteristic point of several typical forms of weld as shown in Figure3[40]. In addition, Zhang et al.[41] used laser structured light scanning to obtain 3D features of workpiece and complex and long seam scan path designing by multiple segment scanning shown in Figure4.

Cross line laser used in many application such using cross line laser to get welding height measurement of the tube to tube sheet welding experiment plate[42]. Zhang et al.[43]also used cross line laser for weld line detection where the projector consist of two orthogonal red laser beams to get 3D information of workpiece as shown in Figure5.

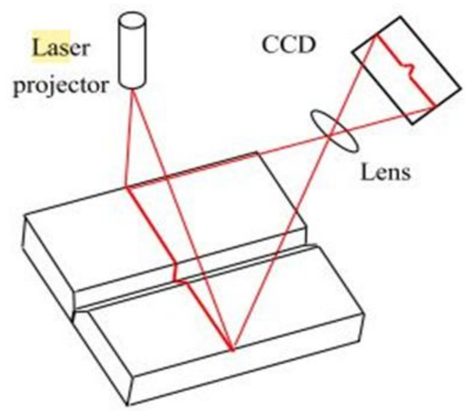

Figure1: Location Identification of Single -V groove Butt Joint by Laser Projectors and Camera [36].

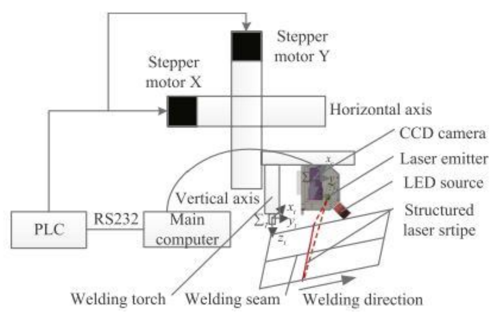

Figure2: Seam Tracking of Narrow Butt in the Vertical and Horizontal Direction [41].

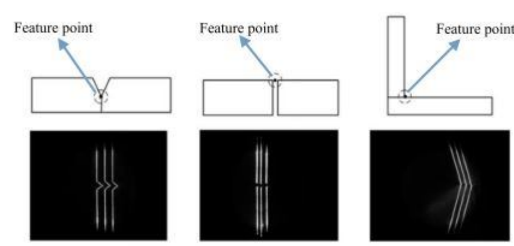

Figure3: Characteristic Point of Several Typical Forms of Weld [40]

III. DETECTION PRINCIPLE OF LASER VISION SENSOR

Visual system based on combination of laser structured light is belonging to the category of Active stereo vision, which use a camera and additional light to get 3D spatial parameters of the object[44]. The measurement principle of visual system based on laser structured can be divided into two categories: laser triangulation and optical triangulation.

A. The Principle of Laser Triangulation Measurement

In recent times, there have been an increasing in the field of automations, machines tools, papermaking, and construction of the usage of non-contact optical instruments based on laser triangulation. the optical path design of laser triangulation method should meet the Scheimpflug condition to get the best effect and measurement accuracy, which mean that image plane, object plane, and the main surface of the lens must have common line. According to the incident angle of the laser transmitter, laser triangulation can be divided into two sorts which are direct and oblique as shown in Figure6**.** The oblique laser triangulation method is more suitable for measuring objects with a surface close to a mirror surface, and it has a higher resolution than direct pattern with the disadvantage of a smaller measurement range and a larger volume and specular[45]. The measurement principle of oblique laser triangulation method will be illustrated below:

$$\delta = \frac{l_1 D \sin(\theta_1 + \theta_2)}{l_2 \sin \emptyset \cos \theta_1 + D \sin(\theta_1 + \theta_2 + \emptyset)} \qquad (1)$$

Where Ø the angle between the photodetector axis and imaging lensaxis, δ is the offset distance of the image on the photosensitive surface, D is determined depth of the object, L1 is the distance of the image, L2 is the distance of the object, θ1 is the angle between the beam of the laser axis and normal plane, θ2 is the angle between the axis of imaging lens and normal plane. θ_1, θ_2 and ϕ should meet the Scheimpflug condition to ensure that the measured point is imaged on the photosensitive surface [45].

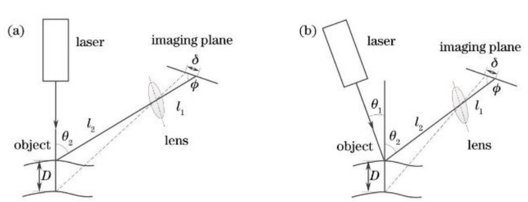

Figure.6: (a) Straight Incidence Mode; Figure (b) Oblique Incidence Mode [45]

The direct-type laser triangulation method is good for measuring sort of surfaces that has a good scattering performance. To improve the performance and increase an accuracy, the angle betweenthe scattering angle ϴ,lens, and CCD plane should meet the Scheimpflug principle, because the plane of image, object and lens must intersect on a straight line as illustrated on equation below[46]:

$$\tan\theta = \beta \tan \emptyset \qquad (2)$$

*B*is the lateral magnification. According to the principle of triangle similarity, the relationship between the actual displacement of the object Δ and the displacement of the image point δ is[46]:

$$\Delta = \frac{l \sin \emptyset \delta}{l' \sin\theta \pm \delta \sin(\theta + \emptyset)} \qquad (3)$$

where*L*is determined as the distance between the object and lens, *L*`the distance between lens and image as shown in Figure7.

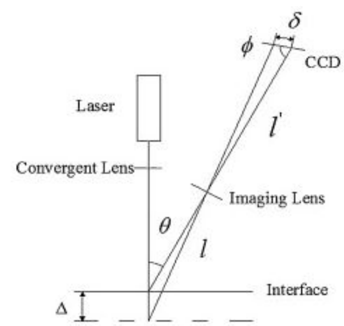

Figure.7:The Principle of Direct Laser Triangulation Method[46]

B. The Measurement Principle of Optical Triangulation

The optical triangulation based on the principle of small-aperture imaging has a lower accuracy than the method of laser triangulation. According to the structural design, the optical triangulation method is divided into three categories: Perpendicular incidence-oblique receiving, oblique incidence -perpendicular receiving, and oblique incidence-oblique receiving. Taking oblique incidence -perpendicular receiving as an example to analyze its measurement principle. Schematic diagram of the system and pinhole imaging model is shown in Figure8[45]. The 2D coordinate system uo_1v is the image coordinate system, 3D coordinate system xyz is optical coordinate system and $o_1o_2$is the equivalent focal distance*f*. Let the coordinate value of the point *P*to be measured in the optical coordinate system xyz be (x, y, z), which the coordinate value of the imaging point*P*in the image coordinate system uo_1v is (u,v), then the system measurement principle isillustrated below[45]:

$$X = \frac{-Hu \tan\theta}{f \tan\theta + u} \qquad (4)$$

$$y = \frac{-Hv \tan\theta}{f \tan\theta + v} \qquad (5)$$

$$z = \frac{Hu}{u - f \tan\theta} \qquad (6)$$

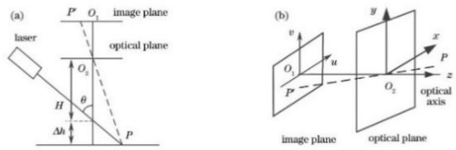

Figure.8:TheMeasurement Principle of Optical TriangulationMethod (a) Schematic of System (b) Pinhole Imaging Model[45]

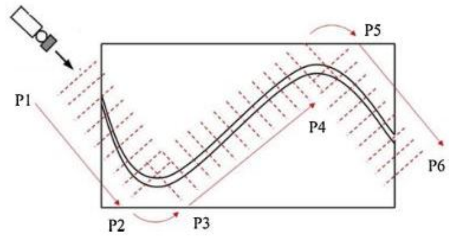

Figure 4: Design of complex long seam scan path [41].

There are many methods of conducting the physical structure of laser vision sensor that have been used to detect a various type of groove and each one has it features, Table 1. illustrates the different types of techniques, and the advantages and disadvantages of each methodology that have been used for seam tracking of active vision based.

Table 2. Measurement Modeling Methods and Various Parameters that Used in the Papers.

Ref	Author/Year	The Measurement Method	Workpiece/Thickness	Type of welding	Weld joint
[33]	2012	The principle of laser triangulation	coupon /15.9 mm	-	Different type.
[43]	2014	The principle of laser triangulation	a wind power tower	-	T-intersection
[47]	2016	The principle of laser triangulation	Metal	a tungsten inert gas	weld bead
[48]	2016	A grid structured laser vision sensing	A steel	welding robot	V groove
[49]	2016	Self-creating template algorithm & modified template matching	Metal /9mm	-	V-groove
[50]	2017	The principle of laser triangulation	carbon steels/10mm	TIG	V groove
[51]	2017	using a cumulative gray frequency	carbon steels/10mm	TIG	V groove
[52]	2017	Based on support vector machine (SVM)	Metal	-	Different type.
[53]	2018	The digital light processing projector	-	Arc	Different type.
[34]	2018	Traditional optical triangulation	1.5 mm	Laser beam welding (LBW)	butt joint
[38]	2018	Based on laser triangulation principle	metal	-	weld bead
[36]	2018	Based on laser triangulation principle	ship hull plate	-	T-shaped weld
[37]	2018	principle of small hole imaging	-	(MAG) Arc Welding	Butt welds, Lap and Complex curve welds.
[54]	2018	The principle of optical triangulation	-	-	cross- sectional groove
[55]	2018	Based on the principle of initial weld point guiding method	Metal	The shielding gases (MIG)	curved surface and planar micro-gap weld
[39]	2019	The principle of optical triangulation	Metal /2mm	Shielding gas (MIG)	narrow butt joints
[40]	2019	Ideal pinhole imaging	-	MIG	Different type
[56]	2019	The principle of optical	2 mm	Laser beam welding (LBW)	butt joint

		triangulation			
[57]	2019	on pinhole imaging principle	-	Shielding gas (MIG	weld bead
[42]	2020	Linear regression equation of least square method	tube sheet/950mm and 40 mm	TIG	tube-to-tubesheet

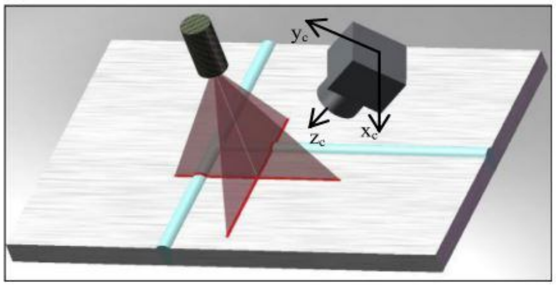

Figure.5: A cross-line Detection[43]

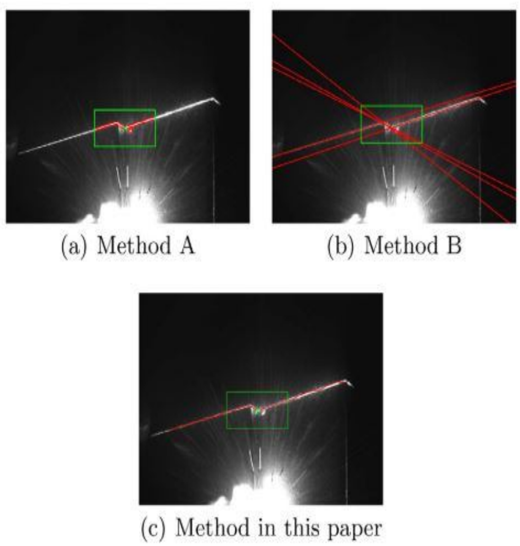

Figure. 11: The Comparative Experiments of the Applied Algorithms Method [58]

IV. ACQUISITION AND IMAGE PROCESSING

The image processing is one of the essential parts for extracting the image features[59]–[67].The image processing of the weld seam tracking is going through several process that is involving smoothening, extracting the features and so on. The processes are applied after image acquisition. The image acquisition will be through vision senor that capture the object based on the calibration of the Camera and laser. After getting the image, the features of the image inweld seam will be extracted by algorithms of image processing, and there are many image algorithms that involve many steps like filtering and smoothing, background elimination, threshold segmentation, edge detection, and feature extraction [62]**.** Image processing for narrow butt seams with width less than 0.2 mm involvemedian filter and min operation to remove the noise**,** ROI computation of the laser and weld seam is going to be by assembling the pixels of the gray value in each column and row, and there are three steps for extracting the features including the extraction of center profile by gray centroid method, Hough transform to get the accurate features line, and least-square fitting for increasing the two features lines that obtained by Hough transformation[39].

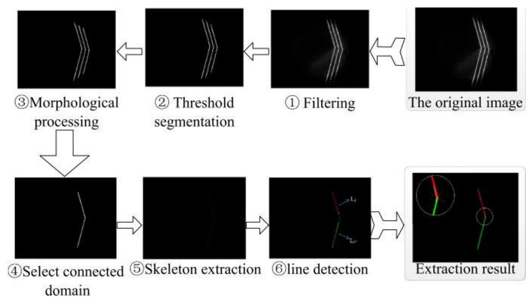

Figure.9: The Steps of Image Processing [40]

Yanbiao Zou used algorithms for detecting seam tracking that for extracting the image features. This algorithm is based on deep convolutional neural network, narrow band-pass filter for removing the noise of the weld seam. The steps for extracting the features are shown in Figure9.

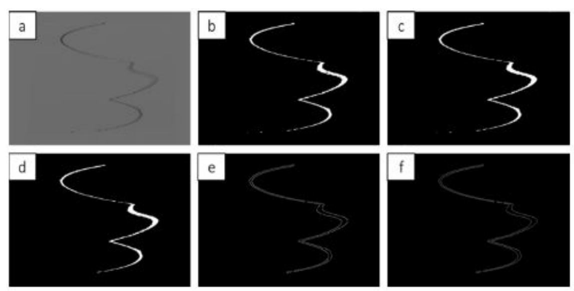

Figure.12: The image processing of weld: (a) Filtering; (b)Binary image; (c) smoothing; (d) Domain filtering connection; (e) Edge detection; (f) fine-tuning.[41]

Method for locating the features points, binary morphology processing for eliminating the interference of line segments and isolated points, skeleton extraction for achieving effective extraction of centreline of the laser stripe, a line detection algorithm is performed for fitting the straight line of the skeleton line, and there is a combination between the fitting data and characteristic parameters[40]. In addition, Yan Biao Zhou proposed a real time pose estimation method for weld seam tracking by building point cloud data and the construction of real time tool coordinate system and getting rotation angles which involve efficient convolution operators (ECO) for tracking, integration and adoption of a support vector machine (SVM) with morphological intersection method for classification of the image with robust noise to better suppressing the draft of tracking model, the method of morphological intersection for position determination of several intersections and the steps of it are shown in Figure10 [35].

Nianfeng Wang did a comparative experiments for weld seam recognition which is based on three methods to extract the features of the lap, butt ,and fillet weld with spatter, first method based on geometrical features(method A) and the accuracy of detecting fillet weld is 99.33%, second method is using the Hough transform (method B) and the accuracy of detecting fillet weld is 98.00%, the third method (method C) is the proposed algorithm and the accuracy of detecting fillet weld is 99.33%. the third method (method C) is the proposed algorithm for a weld seam recognition that involve three steps: To recognize the initial laser center line, they used Laplacian Gaussian filter. The algorithm was based on model of NURBS-snake for the detection of the online laser center, segmentation and straight-line fitting for the extraction ofusing a Laplacian of Gaussian filter to recognize the initial laser center line, the algorithm is based on the model of NURBS-snake for the online laser center line detection, segmentation and straight-line fitting for the extraction of weld feature as shown in the Figure11 is the applied algorithm and the performance of the three methods to the same welding process [58].

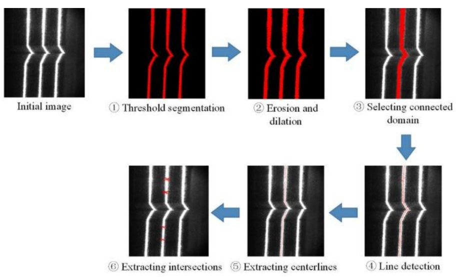

Figure.10: Morphological Intersection Method Steps [35]

V. CURRENT CHALLENGES

From the analysis of the review, the most current challenges of laser vision sensor are assembled and concluded asfollow:

- In the combination of passive and active methods for detecting the weld joint, the hybrid vision sensor for detecting the weld joint like butt joint had a preview distance, which means the calibration is still one of the challenges in the weld seam tracking.
- One of the major challenges is the realization of the seam online while there is a strong reflection and noise, where the common image processing techniques are not robust enough to distinguish between the target stripes of the laser and the reflected one.
- Although laser structured light has many advantages like simple, highly precise, and obtaining 3D position easily, and so on. However, they are very sensitive to the change or the position. Therefore, inclination, and measurement environment, roughness, and color arethe most factors that influence the accuracy of the detection
- For detecting the weld joint, it has been seen that the width is constant in most of the published articles. However, it is not always constant, it varies depending on the application of it.

VI. CONCLUSION

This review paper has assembled and summarized the recent studies and research progress of visual sensors based on combination of laser structured light in weld seam tracking. It also summarized the different measurement methods for extracting the image features. Moreover, the various image processing algorithms and types of laser structured light have been discussed in this paper. Overall, a visual sensor based on laser structured light has its own advantages in weld seam tracking. It can extract accurately the image features, the image processing is applicable, and time performance is good enough to make the system is fully automated. Now, the research trend in active vision is using laser structured light as auxiliary light because of its characteristics on stability, accuracy, and time performance. However, the high price, and the monopoly of the market, inability of detecting and exercising the image features in the molten pool limit its application.

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