Integrated sensors for robotic laser welding

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Abstract
A welding head is under development with integrated sensory systems for robotic laser welding applications. Robotic laser welding requires sensory systems that are capable to accurately guide the welding head over a seam in three-dimensional space and provide information about the welding process as well as the quality of the welding result. In this paper the focus is on seam tracking. It is difficult to measure three-dimensional parameters of a ream during a robotic laser welding task, especially when sharp corners are present. The proposed sensory system is capable to provide the three dimensional parameters of a seam in one measurement and guide robots over sharp corners.

Keywords: Sensor integration, seam tracking, robotic laser welding

1 Introduction
The use of robotic laser welding is becoming widely spread, mainly due to its ability to weld in three-dimensional space. To enlarge the range of applications it should be possible to achieve welding velocities as high as 250mm/sec. Therefore there is a growing demand for sensory systems that are capable to efficiently guide the laser welding tool over the work piece at high velocities in three-dimensional space. It is essential for these sensory systems to be compact to increase accessibility, and they should also be able to perform additional functions such as process control and weld inspection.

These requirements introduce the need for integration of various functions in a compact tool. Such a laser welding tool is under development. Within this paper the process of seam detection and the sensor’s initial calibration functions will be elaborated.

2 Sensing methods overview
There are a number of methods to implement each of the laser welding functionalities with the use of different types of sensors (tactile, ultrasonic, electromagnetic, etc) [1, 2]. Still only few of them can be equally efficient when used for each of the three required sensor functionalities (detection, inspection, process control).

The majority of available sensors make use of optical means (imaging sensors, structured or other type of light) and triangulation methods to obtain the required information [3, 4, 5]. For the three functionalities that are important to laser welding different light sources and imaging means are required.

In general for seam detection, a combination of a imaging sensor (camera) and a projected structured light shape is used. The structured light is projected under an angle in relation to the camera, and therefore triangulation can be used to determine the position of the projected shape. Discontinuities along the structure light shape reveal the position of the weld joint. Uniform light is also required for seam detection at the cases where the structured light is not deformed in any way, for instance the butt joint configuration.

For seam inspection, the same combination of structured light and camera can be used, where detection of discontinuities and deformation of the structured light can provide information about the surface quality of the weld. Additionally, uniform light can also be used to provide images where texture analysis can improve the quality estimation.

For process control, quite often process light is observed at different wavelengths using photodiodes or even cameras [6].

3 Seam detection problem
Seam detections is the ability to accurately identify the position and orientation of a weld joint in relation to the high power laser tool centre point (TCP). Even though the use of robots increases the accessibility and the capabilities of the welding processes, it also adds additional parameters that need to be taken into account for the seam detection and tracking process. A number of challenges of robotic laser welding and laser welding in general are outlined next.

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3.1 Joint configurations

There are several different joint configurations (Fig.1) that might be required to be detected, each configuration with its own properties. Depending on the properties of each configuration a specific detection method can be implemented.

Fig.1: Samples of joint configurations from left to right, butt, overlap and corner joint

3.2 Sharp corners paths

The appearance of sharp corners along a weld path can influence the detection process. Many seam tracking sensors use a structured light source that projects one or more lines on the work piece. These lines are approximately perpendicular to the seam. With such a light source it is very likely that the seam tracking fails after the occurrence of a sharp corner illustrated in Fig.2.

Fig.2: Inability to detect corners using a structured light shape of only a single line

3.3 Tool position & orientation acquisition

The relative position of the tool towards the work piece in three-dimensional space consists of three positions and three orientations. Most measurement techniques can not acquire all data in one measurement. The number of adjustment measurements that are required for the identification of the complete tool positions and orientations depends on the projected light shape and triangulation method that are used.

3.4 Robot dynamics and kinematics

The majority of the sensory systems are orientation depended. Therefore the sensory system has to keep a certain orientation in relation to the orientation of the weld joint (see e.g. Fig.2). To track sharp curves and to keep the sensor in the correct orientation, the tool has to rotate very quickly. In such cases robot dynamics will influence the accuracy of the welding process.

3.5 Sensor speed

For seam teaching, the required time for the seam detection is usually not so important, as the joint path can first be taught and then replayed. For real-time seam teaching however, the measurements take place at high processing velocities and the data has to be available in time to correct path errors. That makes the speed of the detection process an important parameter for the robotic implementation of the laser welding processes.

4 Developed prototype

The developed prototype is designed as a platform for implementation and testing of the required laser welding functionalities. At its current state the prototype consists of a laser welding head, six mounting bases and three laser diode holders (Fig.3).

Fig.3: Developed prototype platform

The six mounting bases can be used for the installation of optics, cameras or light sources that are necessary for each functionality. One mounting base is used to attach an interface for the connection with the robot tip.

The welding head carries a mirror that can be rotated towards each of the mounting bases. Thus it can provide a camera with a coaxial view to the high power laser optical path. The mounting bases and coaxial camera can also be used by Illuminations sources or any other system that requires acquiring or projecting coaxially to the high poser laser beam.

The three laser diode holders are used to mount the structured light projectors. Each holder allows the projection of the structured light with a specific angle, as well as the adjustment of the diode’s focus lens.

The structured light that the laser diodes project is line shaped. When three of them are projected under and angle and perimetric the high poser laser TCP, the resulting structured light shape forms a triangle (Fig.4).

A camera provides pictures of the formed triangle and its characteristics are measured with the use of image processing algorithms. Changes in the size and the shape of the structured light shape can be measured and provide information about the position and orientation of the tool in relation to the work piece. Deformations and discontinuities along the boundaries
of the structured light shape can provide information about the position of the weld joint (for seam detection) and the quality of the welded seam (seam inspection).

5 Sensor calibration

Depending on the configuration of the laser welding system, additional calibrations might be required for the correct functionality of the sensor. For instance, different high power laser focal distance may be required for different welding processes. A change of the high power laser focus lens results in changes of projection angles of the laser diodes and in a change of the optical path to the camera. The latter gives rise to a different magnification and different lens distortions.

5.1 Lens calibration

The focussing lens for the high power laser is not optimised to generate distortion free images with large field of view. This could result to distortions especially near the borders of the image (Fig.4 left). For accurate measurements it is necessary to be able to identify these distortions and use the information to undistort the image.

Several lens calibration techniques are available in literature. In Fig.4 the original image is compared with an undistorted one that is the result of the calibration method found in [7] is displayed.

Fig.4: On the left the origial image where visibly the lines are distorted, on the right the undistorted image

5.2 Sensor calibration

The purpose of the sensor calibration is to obtain the parameters in the mathematical expressions that relate features in the camera images with actual three-dimensional positions and orientations. The input of the calibration consists of images with triangles as in Fig.4 that are observed when a perfectly flat surface is positioned underneath the welding head.

Since the structured light laser lines are being projected under an angle, they form a three dimensional shape which enlarges when the surface is close to the welding head and converges in the opposite direction. As the structured light shape is triangular, there can be only one converging point in three-dimensional space.

The sensor calibration process requires that the projected triangles corners can be detected. This task is implemented by applying image processing algorithms (paragraph 7) on the images that are captured by the camera. An additional requirement of the sensor calibration process is to have the optical axis of the high power laser perpendicular to a flat surface. It is assumed that this can be achieved somehow.

For the calibration a series of images is acquired while the robot positions the tool at a number of positions. By displacing the tool along the optical axis a different size of the same structured shape is projected on the flat surface. By acquiring the coordinates of the corners of the shape and combining it with the relative displacement of the tool, a number of three dimensional corner coordinate data is obtained. Then a line fitting implementation on the data is performed. This results to the equations of the lines that the corners points describe in three-dimensional space (Fig.5)

Fig.5: Calibration data and fitted lines

From the acquired lines the projection angles of the corner points as well as the coordinates of the point can be calculated.

6 Sensor process

6.1 Position and orientation

With the completion of the calibration, it is possible to calculate the actual position and orientation of the welding head in relation to the work piece. This is implemented by comparing the work piece plane’s orientation and position with the desired orientation and position that the plane should obtain. In this section the measurement procedure is outlined for a work piece with a flat surface. Therefore, it is necessary to define a “virtual” plane $P_{\text{Vir}}$ that carries the information about the desired position and orientation. This virtual plane can be expressed with following equation:

$$D_{\text{VirX}}x + D_{\text{VirY}}y + D_{\text{VirZ}}z - D_{\text{Vir}} = 0$$

and its normal vector is defined as:

$$n_{\text{Vir}} = \begin{bmatrix} D_{\text{VirX}} \\ D_{\text{VirY}} \\ D_{\text{VirZ}} \end{bmatrix}$$

The welding head’s camera is continuously capturing images of the projection of the structured light on the work piece. For each image, the triangle corners points are acquired. These three corner points also define a plane $P_{\text{New}}$ in three-dimensional space and a normal vector $n_{\text{New}}$. The $P_{\text{New}}$ is actually the plane of the work piece.
As was previously mentioned, the objective is to be able to determine the orientation and position of a work piece in relation to the welding head. This is being implemented by calculating the dihedral angle between every new plane and any user defined ‘virtual’ plane that holds the desired position and orientation. The dihedral angle between the two planes can be then calculated via the dot product of the plane normal vectors.

In Fig.6, the angle that is formed between two surfaces is displayed. Additionally, the normal vectors $n_{\text{Vir}}$ and $n_{\text{New}}$ of the virtual and “new” work piece planes are also displayed. As was mentioned before the angle between the normal vectors is equal to the angle between the planes. Still the problem that remains is the axis around which the new plane should be rotated to become parallel to the calibration plane.

![Fig.6: Normal vectors & Rotation axis](image)

When the two normal vectors are set on a common starting point, they form a plane. The dihedral angle “0” belongs to that plane. Therefore, it is required to rotate the image plane around an axis which is perpendicular to the plane of the normal vectors. This axis can be derived from the cross product of the two normal vectors $n_{\text{Vir}} \times n_{\text{New}}$ as shown on Fig.6. This axis is also parallel to the line that is formed from the intersection of the two image planes. The origin of this rotation axis is placed at the point where the z-axis of the sensor coordinate system penetrates the virtual plane.

6.2 Seam detection

For the seam detection process it is necessary to have prior information about the configuration of the weld joint. As it is already mentioned in paragraph 4.1 the seam detection is based on discontinuities or deformations of the structured light shape (Fig.7).

![Fig.7: Deformations of structured light due to different joint configurations](image)

Depending on the joint configuration, different detection algorithms need to be used. For instance, in the case of overlap joints, discontinuities appear along the structured light lines, whereas in the case of butt joints, nothing changes along the structured light shape and therefore other ways of detection need to be used (Fig.8).

![Fig.8: Examples of projected structured light on overlap joint (left) and butt joint (right)](image)

7 Image processing

7.1 Introduction

The main goal of image processing is the identification of the existing lines in the captured images. Once the lines have been identified the relative position and orientation of the tool to the work piece and the seam can be calculated as was explained in paragraphs 6.1 and 6.2.

For the correct interpretation of the line detection results, prior knowledge of the joint configuration under detection is also required. For instance, in image Fig.8.a the seam position can be detected from the discontinuities along the structured light shape, whereas in image Fig.8.c the seam can be detected from the bending parts of the lines.

The accuracy of the image processing measurements depends on the resolution of the imaging sensor and the accuracy of the processing algorithms. Image processing is a time intensive process, therefore a greater accuracy usually requires more time. For this
reason, the obtained accuracy may be reduced when high measurement frequency is needed.

7.2 Image processing algorithms

In Fig.9 some of the main image processing steps for the detection of the lines and the acquisition of their junction points are being displayed.

8 Experimental results

8.1 General Overview

In Fig.10 an example of a seam detection output image from the developed sensory system is displayed. At this example the seam detection has been performed on overlap joint configuration. As expected, discontinuities along the structured light shape are evident. The separate parts of the triangular shape have been labelled and displayed in Fig.10 with different grey values (white, and dark grey).

The detected lines of the triangular shape are also displayed along with their junctions on the corner points A, B and C. These are the points that will be used for the identification of the orientation and position of the welding head in relation to the work piece.

8.2 Orientation free overlap joint detection

As was mentioned in paragraphs 3.4 the requirement to keep a certain sensor orientation relative to the seam can introduce problems due to robot dynamics. In Fig.11, examples of seam detection cases are displayed where the orientation and position of the seam is detected regardless the orientation of the sensor. The joint configuration in Fig.11 image series is always overlap joint.

The first two images, (a) and (b), of Fig.11 present the original image and the resulting image with all the detected lines, triangular shape’s corner points and seam detection points and line. Fig.11.c displays only the necessary information which is the corner points of the triangular shape (green) and the seam detection points (blue). In Fig.11.d the detection of the seam in a different position through the triangular shape..
is presented. Finally, in Fig.11.e and Fig.11.f the detection of the seam with different orientations is displayed.

8.3 Sharp corner detection of overlap joints

Another challenge that the seam detection sensors face is the existence of sharp corners. In Fig.12 a series of images are presented that display the detection of sharp corners along a seam. For this image series a sharp corner was placed under the sensor and was asked to be detected.

As it can be seen from the images Fig.12.c and Fig.12.d, the seam detection process of the sharp corners does not differ much from the normal overlap joint case when approached from a static point of view. The identification of the shape of the corner can only be resulted from a seam tracking process, where interpolation of the detected seam points takes place.

9 Conclusions

The developed prototype is capable of seam detection of overlapped joint configurations regardless the seam orientation position or shape. It can extract all the required three-dimensional seam parameters from every single captured image. Still, further optimisations are necessary to speed up the time intensive image processing process.

Bibliography