A fuzzy approach for on-line error compensation during robotic welding

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***Abstract*—During robot welding operations in the manufacturing industry there is a need to modify on-line the welding path due to a mismatch in the position of the components to be welded. These positioning errors are due to multiple factors such as ageing of the components in the part conveyor system, clamp fixtures, disturbances, etc. Therefore, robot reprogramming is needed which requires a stop in the production line and consequently an increment in production costs. In this article, we present an alternative solution to this problem that involves the use of structured lighting using a low-cost laser beam, a CMOS camera and a Fuzzy Controller. To validate the proposed control system, a robotic cell was designed using an industrial KUKA KR16 robot for welding metallic plates. The method was evaluated experimentally under lateral and vertical positioning errors. The control interface includes apart from the misalignment correction, the on/off control of the welding power supply, arc voltage and current adjustment, welding torch speed and the control of the distance between the torch's tip and the welding plate. Obtained results using the experimental design method showed a maximum error of 1.6mm, which is considered appropriate for the welding of industrial beads in metallic plates and which demonstrates the method's effectiveness in practical situations.**

Index Terms - Fuzzy Logic, GMAW, Industrial Robotics, Artificial Vision, Robot Path Control.

I. INTRODUCTION

The welding process establishes an electrical arc between a continuously fed electrode and the weld pool; which is protected by a gas administered externally, hence its name Gas Metal Arc Welding (GMAW) or commonly known as Metal Inert Gas (MIG). During the process, the molten electrode is transferred to the workpiece through the electric arc and serves as the filler metal (weld bead) which is deposited accurately by and automated mechanism, e.g. by an industrial robot. During robot welding manufacturing operations, misalignments are likely to occur. There are several reasons; it can be due to disturbances, positioning sensing errors, ageing of welding fixtures and in general errors in positioning and conveying mechanisms. It is a common practice to make some robot reprogramming to solve the problem that requires the stop of the production line with an increment in production costs. There are currently commercial solutions that can be adapted to solve these common errors, however the costs can be very high, and in the order of the price of the industrial robot itself, which may not be affordable for some small companies. In this article, we present an alternative solution to this problem that involves the use of structured lighting employing a low-cost laser beam, a CMOS camera and a PC-based Fuzzy Controller.

A. Related Work and Objective

There are some examples of robot control for seam tracking. Graf et al. [1] developed a trajectory-based control for seam tracking by modelling the trajectory as a continuous curve in 3D. They showed good results; however, the technique has some drawbacks in cases where the solution does not exist for correcting the orientation of the seam location or if the current robot location is close to the last location. Santti et al. [2] have recently tested high performance processors to extract the dominant line from the segmented data of the trajectory. The system can achieve a line extraction speed of more than 1000 fps, which enables real-time visual seam tracking and robot control. Some approaches that only use an optical sensor have been reported. Liu et al. [3] have proposed to use optical filtering and the modification of the camera's exposure time to extract the geometrical profile of the seam.

The objective of the research presented in this paper is to correct the robot's end effector position online to eliminate the need of reprogramming the robot. In this manner, errors due to disturbances, positioning sensing errors, ageing of welding fixtures and in general errors in positioning and conveying mechanisms are eliminated. Our proposal is based on previous approaches using structure lighting (i.e. laser sensor) and image processing to quantify the misalignment and to react before the actual beam is formed by sending robot commands to reposition the arm robot so that initial offset cannot affect the next piece to be weld in a production line. The performance of the fuzzy controller is verified experimentally.

The paper is structure as follows. In section II, the test bed is explained. The image processing for detecting the part misalignment is described in Section III, whereas the design of the controller and its experimental results are explained in sections IV and V, respectively. Finally, conclusions, current and envisaged work are given at the end of the paper in Section VI.

II. Test Bed

The following equipment composes the test bed: a KUKA robot arm manipulator, GMAW welding station, wire feeder that controls the wire supply to the torch, a PC-based data acquisition system and an inert gas tank as it is depicted in Figure 1.

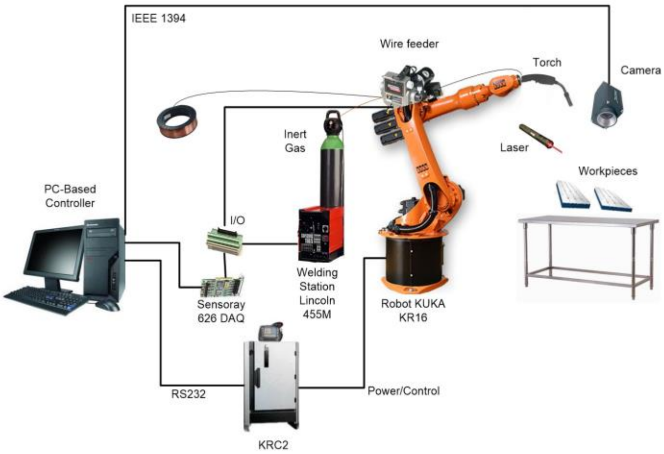

Fig. 1. Welding robotised cell.

The test bed also includes a video camera and a laser sensor oppositely positioned to each other. By using this configuration, occlusions by the torch itself can be avoided. However, an error perspective occurs which is automatically compensated by the proposed fuzzy system. With our proposal, the use of algorithms for perspective error correction and image processing of high computational costs are avoided.

The welding cell is controlled by a PC-based controller. The computer has an Intel Xeon @ 1.86 GHz processor with 3GB RAM that hosts the application interface and which also includes the following functions:

Serial communication for on-line modification of the welding path. The communications is carried out at low-level between the PC and the KRC2 controller using the 3964 protocol.

Image processing. Filtering and segmentation are carried out using a CMOS Basler A602fc camera as input device with an spatial resolution of 656x490 pixels.

Voltage and current modification. The arch current and voltage is modified by DAQ Sensoray 626 using its I/O port. Different I/O signals are used to control the on/off of the welding station, the wire feeding system (including the open/close state of the gas valve), the laser sensor on/off condition, the welding travel speed and the distance from the tip of the torch to the work piece.

The robot manipulator is used in slave mode. During the operations, a robot positioning program is run in the KRC2 controller that continuously search for motion commands from the PC controller in order to start an incremental motion of the robot arm. This program also controls the selection between tool and world coordinates, and the speed and motion step size during incremental motions. The positioning fuzzy controller resides in the PC controller sending the path modification commands to the robot controller during welding operations.

III. Image processing

Typical errors occur when two metallic plates to be welded are misaligned. The first step to correct the situation is to measure this misalignment using image processing tools. Once the positional misalignment is quantified, the information is sent to the robot controller for compensation. The methodology consists of using a laser beam (50 mW with λ = 656nm) aimed to both plates as it is shown in Figure 2.

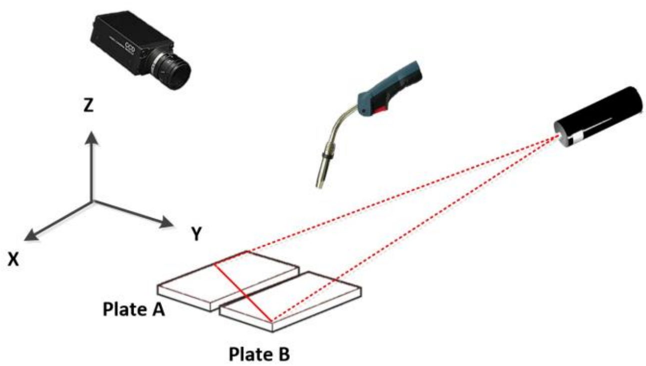

Fig. 2. Welding methodology

When the laser beam is projected onto both plates, a discontinuous line appears and it is captured by the camera sensor as a reference signal. Misalignments can occur in two directions, either they can be lateral misalignments or height misalignments. In both cases, the misalignment is captured in the image. In order to accurately process this information, the image pre-processing is carried out first by smoothing the image applying a mean filter and max/min filtering to reduce noise.

After the pre-processing stage, the image is segmented in the region of interest (ROI) where the necessary information is found (pixel $I_{i,j}$ in Figure 3).

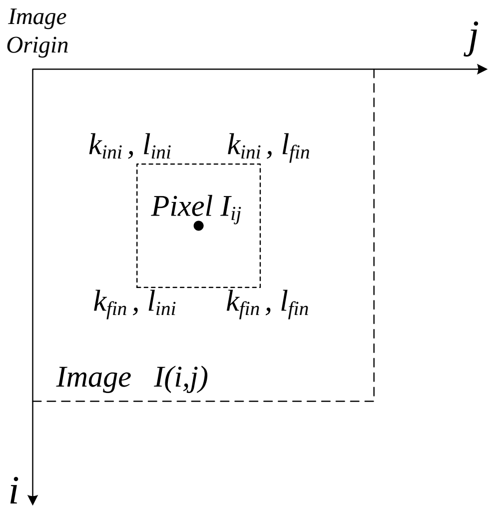

Fig. 3. Image Segmentation

The main idea is to take an image of dimension KxL from the original I image with dimension IxJ, so that I (KxL) < I (IxJ). Having a reduced image in size is also useful to speed up the processing time. The segmented ROI is shown in Figure 4. The gap between Plate A and Plate B can be observed within the rectangle formed by the dashed lines.

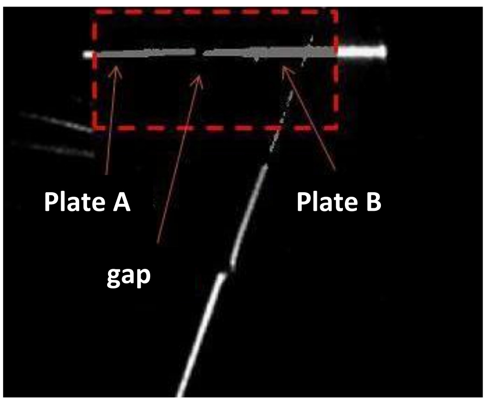

Fig. 4. ROI with segmented image.

Once the gap is determined, the next step is to determine $Discontinuity_1$ and $Discontinuity_2$ from the laser pattern and captured from each plate as showed in Figure 5.

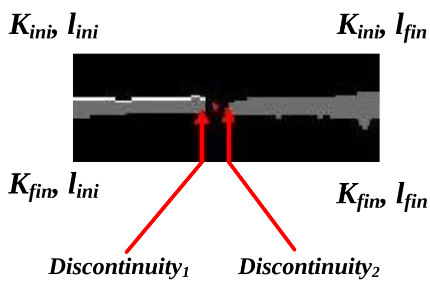

Fig. 5. Discontinuity between plates.

During normal welding operation, the robot's torch should be located in the middle point between the plates as it is indicated (Robot) in Figure 6. In the case of any offset either lateral misalignment or misalignment in the Z axis direction, the point will move accordingly, hence requiring a repositioning strategy.

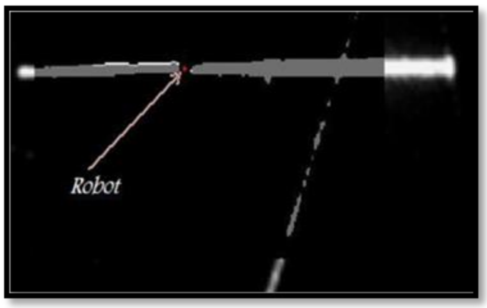

Fig. 6. Point without offset position

In situations where the robot's torch is not in the correct position, the situation has to be assessed first by measuring the misalignment. A corrective motion will be a distance between points union (x,y) and robot (x,y) as depicted in Figure 7. The corrective motion has to be in any direction within 3D space volume, so that we proposed a Fuzzy algorithm to correct it.

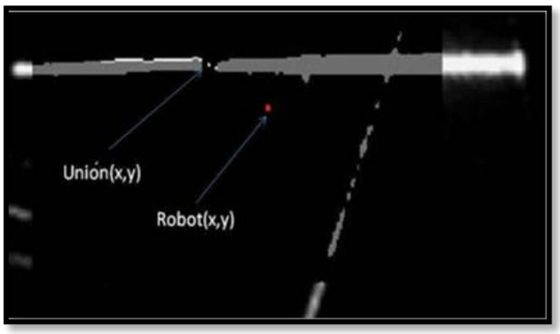

Fig. 7. Torch offset position

IV. DESIGN OF THE CONTROLLER

A. *Input-output relationship*

A fuzzy control in the general case is based on linguistic variables to handle imprecise and vague information. The information is embedded in fuzzy sets that are combined in rules to define actions to be taken as it is indicated in [4] and [5]. In our case, we need to define a set of input-output relationships in order to quantify the positional error of the robot arm with respect to the plate's welding position. In other words, the input information for the robot is the misalignment of the robot's end effector and the output is a robot position command to correct such misalignment.

The design of the tracking system is focused on the offset compensation in automatic production lines, where the parts to be weld are moved by pallets to other welding stations and where typical positioning errors are in the range of few millimetres. These errors are likely to occur between the current workpiece and the next due to several reasons as mentioned earlier. During these circumstances, the user would normally correct the robot path by reprogramming the robot which is time consuming. Our proposal is to carry out the correction on-line, using the same welding program. The idea is to modify incrementally the robot's offset path at the starting of the welding operation should a misalignment is detected so that not reprogramming is needed. In order to modify the path a deviation measurement has to be compared to the original path, so that the robot "knows" where to move to and for how much using linguistic variables such as "right", "left", "far left", "decrease slightly", "increase greatly", etc. The linguistic variables are translated into fuzzy sets with a membership function that considers a value in the range [0, 1].

B. *Fuzzy Design*

The steps to be considered in the design are normalisation, fuzzification, determination of fuzzy rules, defuzzyfication, and denormalisation. The first step is accomplished by using the information given from a sensing system, which in this case is obtained from the laser beam pattern as detected by the camera. This value is read and must be normalised to the range [0,1]. The next step is to fuzzify this information to assess its membership within the fuzzy sets. In our case the variable depends on the workpiece misalignment and we should find its membership function within the following fuzzy sets: far left, left, near left, near, near right, right, and far right.

Once the input data has been normalised and fuzzified, then this is used to build up the fuzzy rules what is meant to be the control antecedent. These rules are built depending on the requirement of the system and after its evaluation their membership function it is determined in relation with the output set (consequent). In order to have useful real values, the data set is defuzzified to obtain a new robot coordinate which is in turn sent to the robot controller to ultimately correct the welding trajectory.

If we consider the X axis to be the welding direction as depicted in Figure 2, it is clear that the misalignment would come only in the Y or Z axis direction. Considering this assumption, the control system is based on two input variables and two output variables. The operation range is defined in the interval [-10, 10] mm in the Y axis and [-5, 5] mm in the Z axis. The zero value is considered to be the reference value for the welding path. Figure 8 shows a set of input data in the Y and Z axes during the evaluation tests of the controller. These values comprise the whole set of values likely to be encountered during operations. For instance, if the algorithm detects a misalignment point (10, -5) it means that the workpiece had an offset of 10mm to the right and -5mm downwards that needs to be compensated.

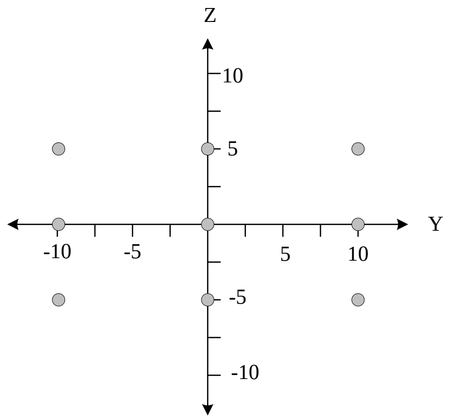

Fig. 8. Robotic motion range for error compensation

The trapezoidal and triangular membership functions are used to design the input and output fuzzy sets as shown in the Figure 9.

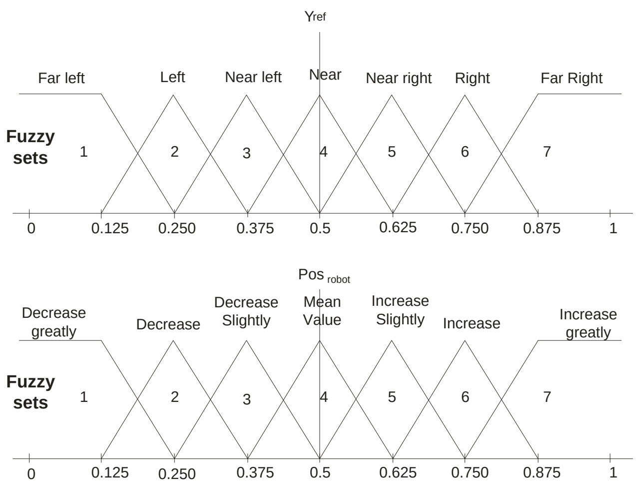

Fig. 9. Fuzzy sets

After the degree of membership of the input values from the input fuzzy sets is defined, the antecedent is created using fuzzy rules as follows:

IF Yref IS Far left	THEN	Decrease greatly Pos_{robot}
IF Yref IS Left	THEN	Decrease Pos_{robot}
IF Yref IS Near left	THEN	Decrease slightly Pos_{robot}
Etc.		

During the defuzzyfication stage the required non-fuzzy real values are obtained using the Centre of Area (CoA) method as a fuzzy conclusion "Y is A". This can be determined by equation (1) in the discrete domain.

$$y = \frac{\sum_i \mu_A(y_i) \times y_i}{\sum_i \mu_A(y_i)} \tag{1}$$

and in the continuous case:

$$y = \frac{\int \mu_A(y_i) \times y_i dy}{\int \mu_A(y_i) dy} \tag{2}$$

where $\mu_A(y_i)$ is the membership function.

Having defuzzified the data, their values are denormalised obtaining a real value which is used as a new robot coordinate. The fuzzy robot controller will also consider other errors related to other variables such as ageing of the positioning mechanisms or disturbances. The correction is on-line, during the welding process avoiding the need of stopping the production line. The operating working range is +/- 10mm in Y axis and +/- 5mm in Z axis. The fuzzy controller was developed in C++ using the Visual Studio compiler.

C. *Performance assessment*

In order to assess the statistical performance of the controller a set of experiments were carried out. The robot path tracking ability during the operation range was evaluated (+/- 10 mm in Y axis and +/- 5 mm in Z axis). The evaluation helps to analyse its behaviour against any variation of the experimental factors. The factors are considered either combined or in its individual form so that the interaction can be identified as indicated in [6]. Care was taken to consider two important aspects during the experimental design that are replicate and aleatorisation. The use of replicates is very important to determine the experimental error. The aleatorisation allows confirming that the random probability variables refer to independent probability distributions. Considering the above assumption, the input variables to the system are the position values that are sent to the robot in the Y and Z axis direction (Dist Y, Dist Z) and as output, the real distance observed in both axes (DistY real and DistZ real).

Experimental design considers variables with two or three levels and k factors referred as to 2^K or 3^K, respectively. In our experiments we decided to use 3^2 with 2 replicates. The decision to use three levels was based on the interest of using the central point within the robot's range motion in both, the Y axis and the Z axis.

V. Results

The experimental procedure can be observed in Figure 10. The experimental set up and the coordinate frame are shown. The offset value (DistY, DistZ) that the fuzzy controller has to compensate is showed in the dashed rectangle. The output value is considered as the real value measured along the main axes (DistY real, DistZ real). It is important to note that the welding seam is applied along the X axis.

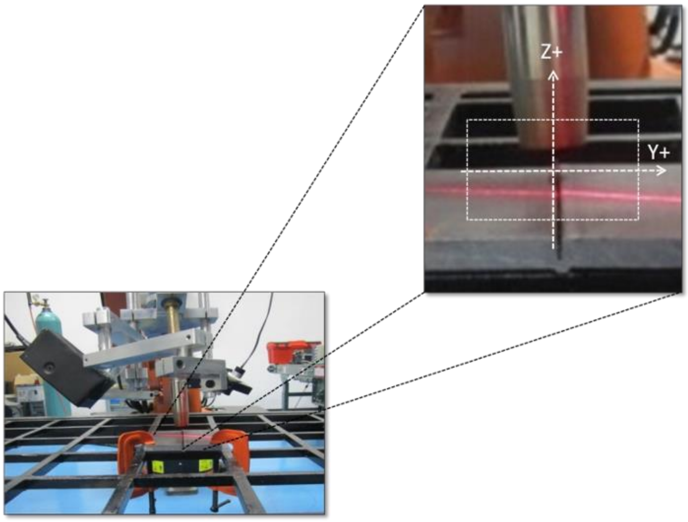

Fig. 10. Experimental set up

Table 1 contains the results from 18 experimental runs. The first 9 corresponds to the first replicate and runs 10 to 18 correspond to the second replicate.

Figure 11 shows results obtained during the correction of lateral misalignment and the measured absolute error. Similarly, Figure 12 shows the obtained results during the correction in the vertical distance and its absolute error. The measured error demonstrates that the robot fuzzy controller compensate the misalignment in all cases. The maximum observed error is 1.6mm in Y axis, which is considered to be appropriate for practical purposes in industrial manufacturing processes.

Table 1: Experimental results and error evaluation (mm)

Dist Y	DistY Real	Error Y	DistZ	DistZ Real	Error Z	Absolute Y error	Absolute Z error
-10	-10.2	0.2	-5	-5	0	0.2	0
-10	-10.4	0.4	0	-0.4	0.4	0.4	0.4
-10	-10.4	0.4	5	4.4	0.6	0.4	0.6
0	0.47	-0.47	-5	-5.26	0.26	0.47	0.26
0	-0.43	0.43	0	-0.42	0.42	0.43	0.42
0	-1.3	1.3	5	5.28	-0.28	1.3	0.28
10	10.6	-0.6	-5	-5.2	0.2	0.6	0.2
10	10.6	-0.6	0	0.6	-0.6	0.6	0.6
10	9.6	0.4	5	5.2	-0.2	0.4	0.2
-10	-9.5	-0.5	-5	-4.95	-0.05	0.5	0.05
-10	-10.2	0.2	0	-0.2	0.2	0.2	0.2
-10	-11.6	1.6	5	4.9	0.1	1.6	0.1
0	-0.53	0.53	-5	-5.3	0.3	0.53	0.3
0	0	0	0	-0.1	0.1	0	0.1
0	-0.33	0.33	5	5.27	-0.27	0.33	0.27
10	10.5	-0.5	-5	-5	0	0.5	0
10	9.6	0.4	0	-0.4	0.4	0.4	0.4
10	9.6	0.4	5	5	0	0.4	0

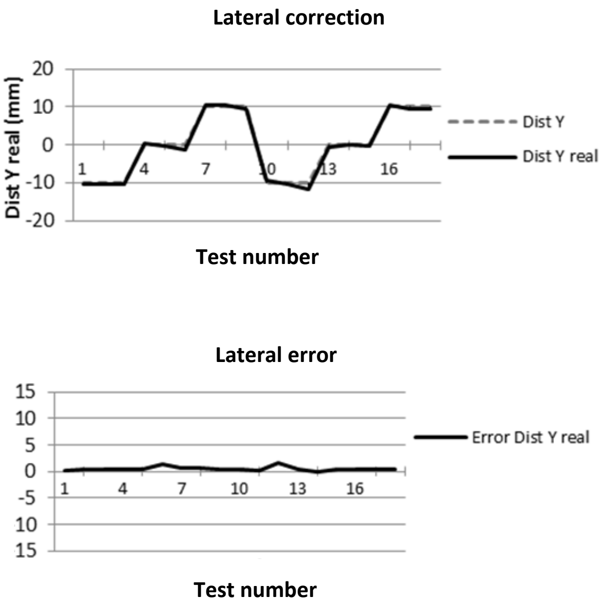

Fig. 11. Lateral misalignment and absolute error

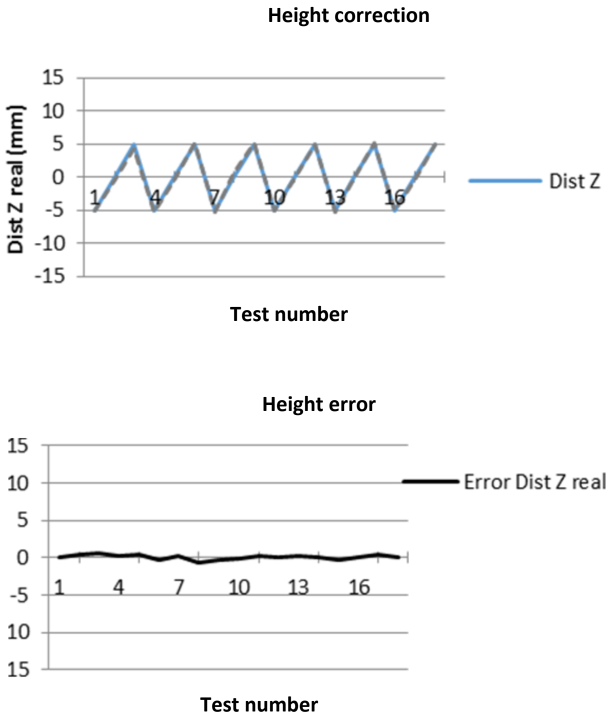

Fig. 12. Vertical misalignment and absolute error

VI. CONCLUSIONS

This article reports a fuzzy controller methodology to correct on-line the misalignment that occurs during welding in production lines. The approach considers structure lighting using a laser beam and a CCD camera. The errors were assessed within the working range (+/- 10mm for the Y axis and +/-5mm in the Z axis). During experiments, the obtained results showed a maximum error of 1.6mm, which is considered appropriate in practical manufacturing tasks. Similarly, a statistical analysis was carried out that showed evidence to consider a mean error value of zero in both axes considering $\alpha = 0.01$, which is an expected offset in production lines with natural variation of the process.

Ongoing work is looking at the use of fuzzy logic type II algorithms using Gaussian membership functions that incorporate the mean and the respective standard deviation so that the noise coming from the sensors is actually considered. Work is also being carried out in seam inspection intending to include the measurement of the seam geometry (thickness, height and depth penetration) and the use of logarithm algorithms to diminish the high luminance encountered during the welding process.

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REFERENCES

[1] Menno de Graaf , Ronald Aarts, Ben Jonker, Johan Meijer Real-time seam tracking for robotic laser welding using trajectory-based control. Control Engineering Practice 18 (2010). pp. 944–953

[2] Tero Santti, Jonne K. Poikonen, Olli Lahdenoja, Mika Laiho, Ari Paasio. Online seam tracking for laser welding with a vision chip and FPGA enabled camera system. IEEE International Symposium on Circuits and Systems (ISCAS), May 2015. pp. 1985 - 1988.

[3] Jinchao Liu, Zhun Fan, Senior Member, IEEE, Søren Ingvor Olsen, Kim Hardam Christensen, Jens Klæstrup Kristensen. A Real-time Passive Vision System for Robotic Arc Welding. IEEE International Conference on Automation Science and Engineering (CASE). Aug, 2015. Pp. 389-394.

[4] Martín del Brío B, Sanz Molina A. (2006). Redes Neuronales y Sistemas Borrosos, 3rd edition. RA-MA, 442p. ISBN 978-84-7897-743-7.

[5] Yen J, Langari R. (1998). Fuzzy Logic: Intelligence, Control, and Information, USA: Editorial Prentice Hall. 548p. ISBN 0135258170.

[6] Montgomery D C. (2007). Design and Analysis of Experiments, John Wiley & Sons, 6th edition. 660p. ISBN-10: 047148735X.

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