Development of a laser-based weld flaw identification system

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Abstract

In this paper, a laser-based flaw identification system is presented for non-destructive inspection of welds. The laser sensor design is based on the laser triangulation principle and the output is a two-dimensional profile of a target sample, which contains basic dimensional information: height and width of the weld. This two-dimensional profile is then processed by a specially devised algorithm based on the local maxima of the sym8 wavelet coefficients accumulation. The positions of artificially created features (notches representative of weld flaws such as surface breaking cracks) on the sample are thereby calculated. It is shown that the laser-based weld flaw identification system is able to reliably and accurately identify and locate surface features ⅓ mm wide.

1. Introduction

Welding plays a fundamental role in many modern manufacturing industries, such as ship building, machinery manufacturing, railway and pipeline construction, etc. The potential weld flaws can significantly deteriorate the reliability of products. Therefore, in order to identify the possible presence of weld flaws, different NDT inspection methods are studied and developed for essential quality control.

Generally, those methods include penetrant testing (PT) (1), eddy current testing (ECT) (2), radiographic testing (RT) (3), ultrasonic testing (UT) (4), magnetic particle inspection (MPI) (5), alternating current field measurement (ACFM) (6) and vision-based inspection. PT (1) can detect surface flaws on both ferrous and non-ferrous metal materials with high sensitivity. However, high levels of surface preparation and cleanliness are required and there are some health and safety issues as well. Additionally, only a relatively nonporous surface material can be inspected. ECT (2) is able to detect flaws in conductive materials, which is excellent in examining continuously welded tubes as in the oil and gas industry but only conductive materials can be tested. Also flaws lying parallel to the probe may be undetectable. Furthermore, the finish of the material might interfere with inspection readings. RT (3) is a widely used testing method to detect both internal and surface flaws for most work pieces with very high sensitivity. However, this method needs well trained operators together with significant cost and safety issues. UT (4) is convenient, inexpensive and well established but requires highly skilled operators to interpret the results, and rough surfaces tend to cause scattering which results in an increased noise detected by the receiver, thus reducing the probability of detection. Moreover, it is very difficult to inspect thin work pieces. MPI (5) has very high sensitivity to detect surface and near surface flaws and is easy to operate. Nonetheless, it is only limited to ferromagnetic materials and proper alignment of magnetic field and flaw is quite critical. ACFM [(6)] can be employed to detect and size surface flaws, albeit, the flaw length needs to be longer than 5 mm. A comparison of the aforementioned techniques is summarised in Table 1.

Table 1: Comparison of commonly used non-destructive testing techniques in weld inspection

	PT	ECT	RT	UT	MPI	ACFM
Non-contact	✗	✓	✓	✗	✗	✗
Materials	Ferrous and non-ferrous metals	Conductive materials	Virtually all materials	Metals, plastics, and wood	Ferromagnetic materials	Conductive materials
Depth of penetration for flaw detection	Surface flaws (non-porous)	Surface flaws	Internal and surface flaws	Internal and near surface flaws	Surface and near surface flaws	Surface flaws (longer than 5 mm)
Cost (capital)	Low	Low	High	Low	Low	High
Operator training level	Low	Medium	High	Medium	Low	High
Interpretation complexity	Low	Medium	High	Medium	Low	High

Due to the technology progress in both computer vision and sensing, vision sensors are capturing more surface flaw detection application space [(7)]. They are well-suited to detect the presence of external weld defects such as reinforcement, root concavity, undercut, sharp corner, incomplete filled groove, root dropout, misalignment of the welded metal sheets, and partial penetration. A significant advantage for using such sensors for surface inspection, compared to other solutions mentioned above, is that it enables an operator to identify potential surface flaws without any contact to a work piece. For example, a vision sensor can be used to track a weld bead on a work piece and measure the 2D profile containing the height and width information of the weld in real time.

In this paper, an inexpensive laser-based weld flaw identification system is presented, including both the measurement system and the flaw identification algorithm. Notches representative of weld flaws, such as undercuts, have been implemented with different sizes on a work piece. The experiments have been done to evaluate the system's intrinsic capability for identifying the weld flaws.

2. Laser-Based Weld Flaw Identification System

The diagram of the laser profilometer system is shown in Figure 1. It includes a laser profile sensor, a host PC and in-house software. The laser profile sensor contains two main parts: a laser projector module and a profile acquisition module. The former emits a laser beam stripe using a low power laser diode (less than 10 mW) with a wavelength of approximately 658 nm onto the weld surface of a test piece. The laser light is then scattered by the surface and reflected back in different directions. The profile acquisition module is used to collect the reflected laser light which contains the 2D profile information of the weld projected on an embedded charge-coupled device (CCD) image sensor.

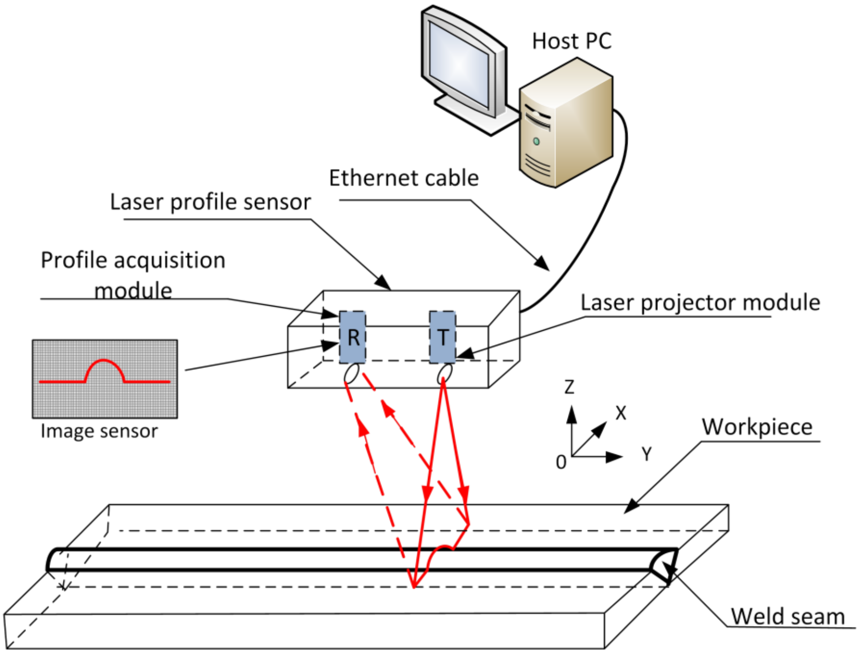


Figure 1: Diagram of the weld flaw identification system

The host PC controls the laser profile sensor to obtain the 2D profiles through an Ethernet cable that can be as long as 100 m. These images are then transferred through the same link in real time to the host PC at a high speed up to 100 frames per second to be analysed by the weld flaw identification algorithm. Once the algorithm identifies any flaw on the work piece, the location of the flaw can be calculated with respect to a defined reference frame.

The profile measurement is based on the laser triangulation principle [8] [9], which is shown in Figure 2. There are two representative points *A* and *B* on the laser stripe (in red line), which are projected from the laser projector module onto the surface of the weld.

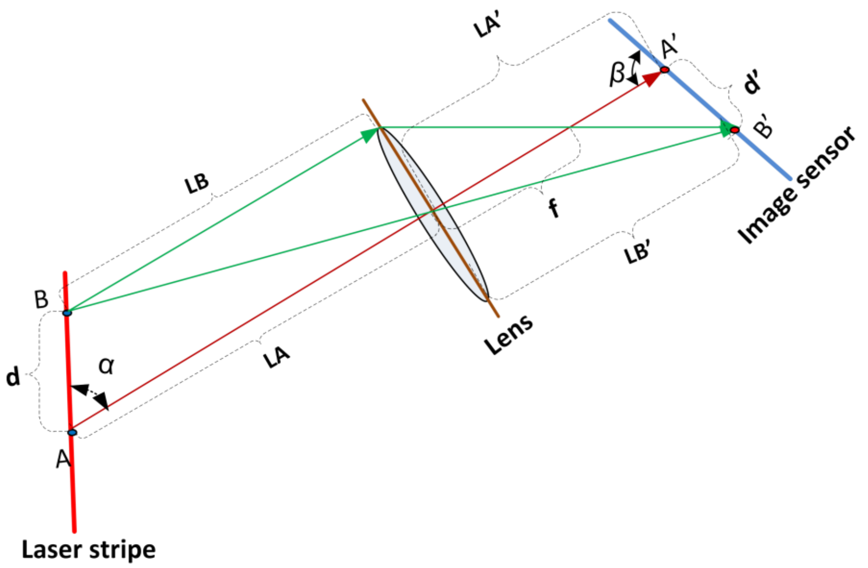


Figure 2: Laser triangulation principle for profile measurement

Point A is on the optical axis (in red line normal to the lens) of the lens and imaged as point A' on the image sensor (in blue line). Similarly B' is the image of point B on the image sensor. d is the distance between A and B while d' is the distance between their images accordingly. LA is the distance from A to the lens while LA' is the distance from A' to the lens. LB and LB' are defined likewise. f is the lens focal length and α and β are the angles between the optical axis and the laser stripe and the image sensor respectively. Thus equations (1) and (2) can be derived using the geometrical relationships:

$$\boldsymbol{LB = LA - dcos\alpha} \tag{1}$$

$$\boldsymbol{LB' = LA' + d'cos\beta} \tag{2}$$

Equations (3) and (4) are obtained using the image focusing law:

$$\frac{1}{LA} + \frac{1}{LA'} = \frac{1}{f} \tag{3}$$

$$\frac{1}{LB} + \frac{1}{LB'} = \frac{1}{f} \tag{4}$$

Therefore the relationship between d, d' can be expressed as:

$$d = \frac{d' sin\beta (LA - f)}{f sin\alpha - d' cos\alpha sin\beta} \tag{5}$$

In the profile acquisition module the focus lens is arranged at a fixed distance and angle from the image sensor to make sure that the image of a laser stripe reflected from the weld at a range of distances can always be focused on the image sensor. Therefore, the positions of the reflected laser points can be determined.

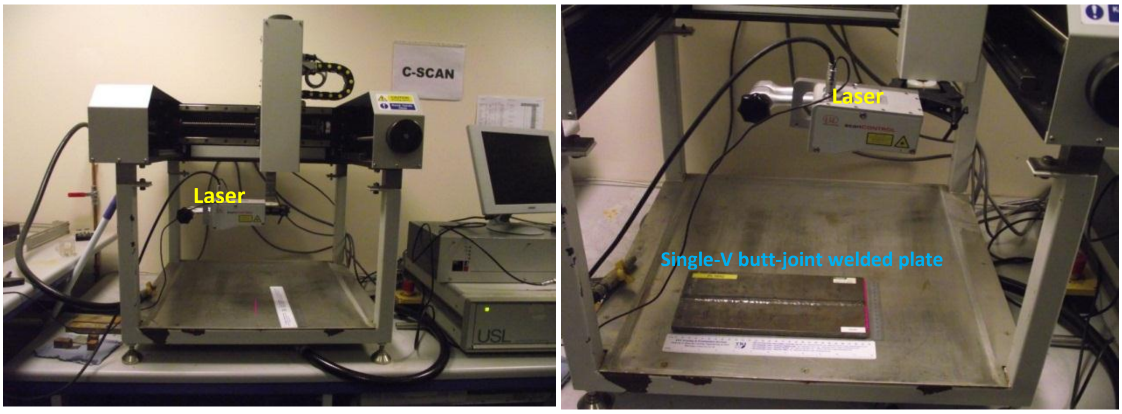
3. Flaw Identification Principle

Wavelet analysis [10] [11] is becoming a common tool for analysing non-stationary signals within time series. The wavelet transform not only has the useful characteristic of time-frequency localisation, but can also automatically adjust the time-frequency window based on the change of signal frequency. It has been proven that the local maxima of a wavelet transform is able to detect the location of irregular structures effectively [12] which can be used to locate a possible flaw besides a weld.

The wavelet transform can characterise the local regularity of a signal where the local regularity of a signal is measured by Lipschitz exponents [12]. The latter represents the smoothness of a signal at a particular point. If the signal is continuously differentiable at a particular point, the Lipschitz exponent of the signal is 1 at that point. However, the Lipschitz exponent is still 1 if the derivative of the signal is bounded but discontinuous at that point. It has been proven [12] that if the Lipschitz exponent is positive at a particular point, the local wavelet modulus maxima will be large for large scales while the local wavelet modulus maxima will be small for negative Lipschitz exponents. Hence, if the coefficients are accumulated at all scales the local wavelet modulus maxima of the singularity points will be enlarged. Thus, by choosing a suitable wavelet and scale based on the principle presented above, the local maxima of the wavelet transform can be computed in order to locate the singularity points in the signal.

4. Results and Discussion

Preliminary trials were carried out to verify the intrinsic capability of the flaw identification system. The experimental setup is shown in Figure 3. A Micro-Epsilon scanControl 2700-100 laser sensor [13] is mounted on a linear stage with three degrees of freedom from Ultrasonic Sciences [14]. The length of laser stripe varies from 76 mm to 148 mm depending on the distance between the sensor and the test piece surface. The resolution can reach 0.12 mm in length (i.e., the distance between each two adjacent points in the total 640 sample points).



(a) 3D linear stage **(b) Sample under test**

Figure 3: (a) Laser-based vision sensor mounted on a multi-axis motion system (b) butt-joint (single-V) welded steel plate

The movement of the 3D motion stage can be controlled by the host PC to a sub-mm accuracy. The laser sensor is used to scan the test sample and transfer the data to the host PC, which uses the proposed algorithm to detect and locate any existing flaws in the vicinity of the weld.

The work piece is a butt-joint (single-V) welded steel plate. It is 300 mm long, 150 mm wide and 10 mm thick with a 15.0 mm wide weld in the middle. On the surface of the work piece, there are two notches as shown in Figure 4. Flaw 1 is 50 mm long, 5 mm deep and ⅓ mm wide. Flaw 2 is 20 mm long, 2 mm deep and ⅓ mm wide.

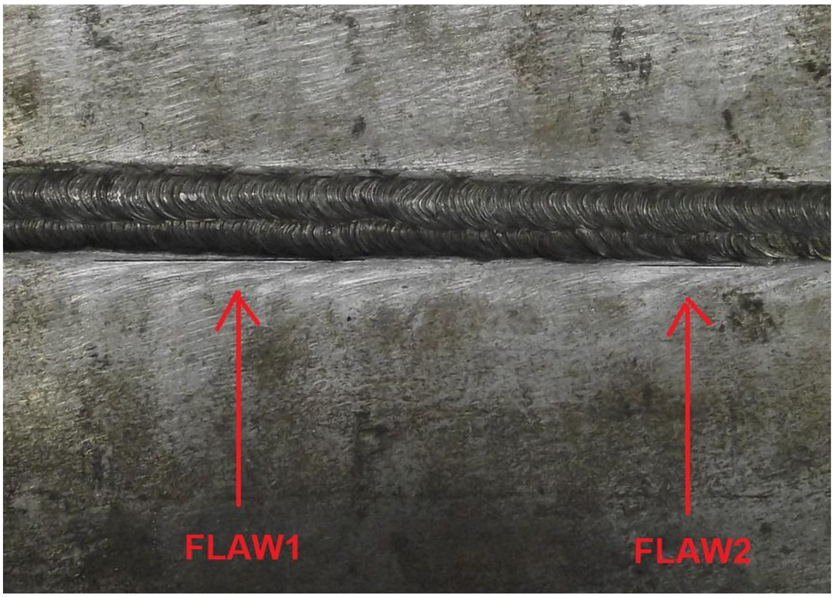


Figure 4: Notches representative of weld surface flaws

In Figure 5(a), Flaw 1 can be observed in the profile obtained near the weld cap. Figure 5(b) shows the continuous wavelet transform (CWT) coefficient accumulation result, which is used to automatically detect and locate the flaw by choosing the local maxima in the wavelet coefficients (excluding the CWT coefficient accumulations at the extremes) using sym8 wavelet. The positioning error of the flaw corresponds to 1 sample point which is calculated to be around 0.12 mm.

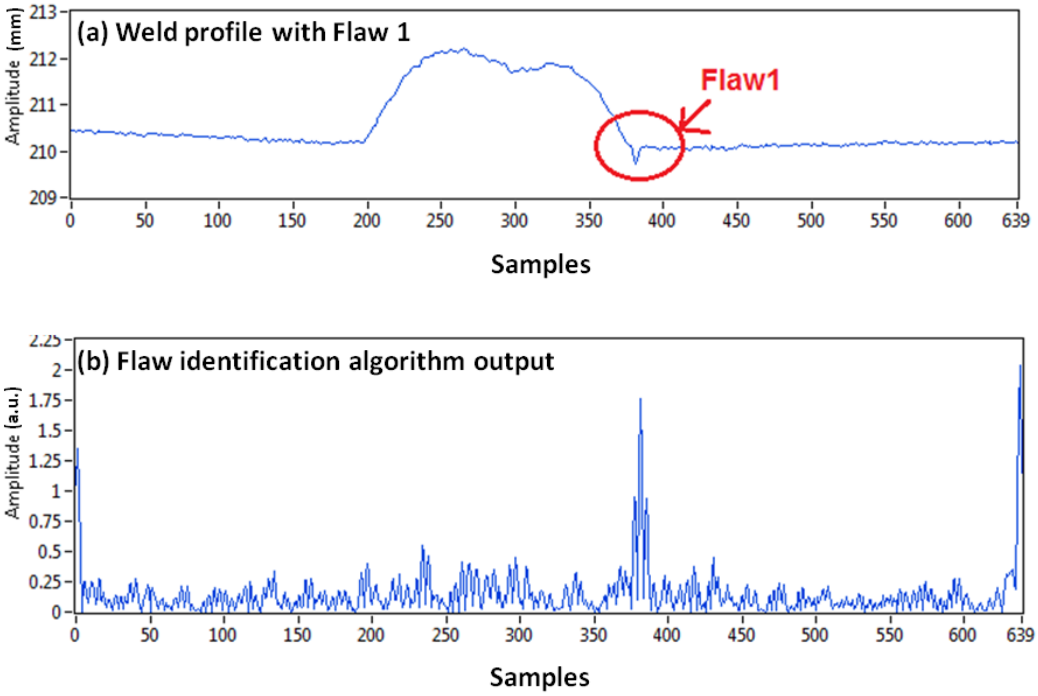


Figure 5: Detection and location of Flaw 1

In Figure 6, Flaw 2 can be observed in the profile of the weld and can be automatically detected and located using the proposed algorithm. Similarly, the positioning error of Flaw 2 corresponds to 1 sample point which is calculated to be approximately 0.12 mm.

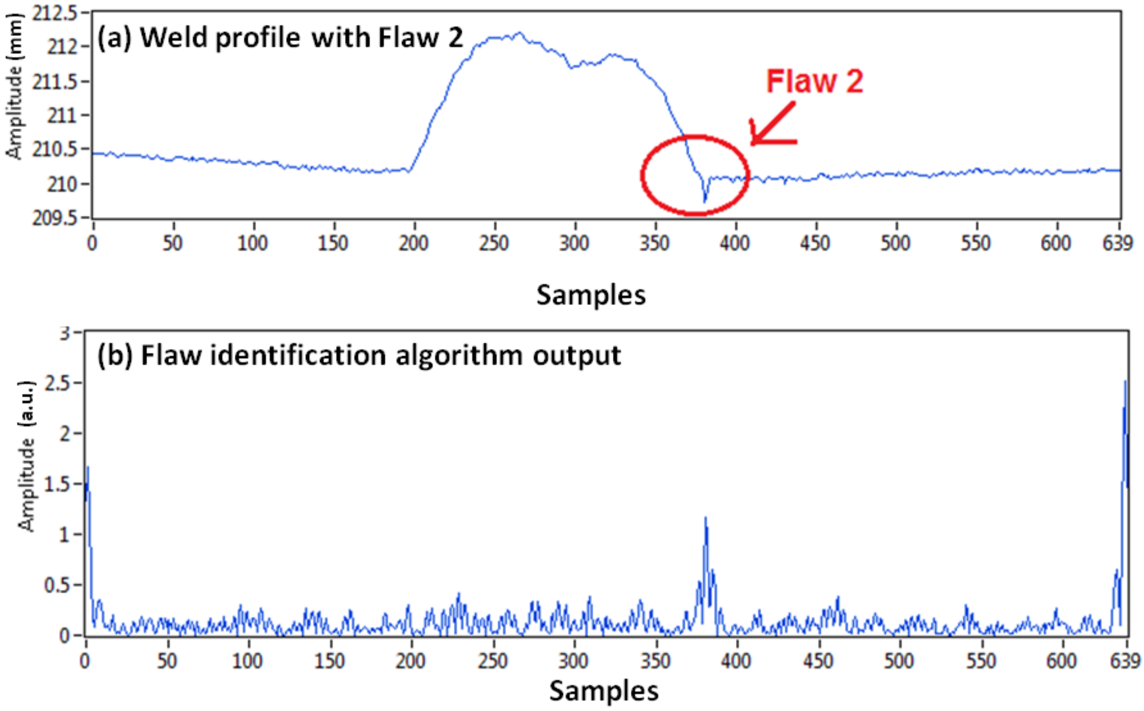


Figure 6: Detection and location of Flaw 2

It should be noted that if there is any uneven part on the weld cap which is of similar size to an existing flaw, it becomes difficult to distinguish the two apart as the algorithm would yield similar local maxima for both. In other words, it may lead to false positives. In which case, an expert vision system based on pattern recognition can be further developed by comparing the profiles of inspected weld with a template of a sound weld profile. Furthermore, as the laser stripe is projected on the surface of the weld and the profile measurement result is determined by the reflected laser light, the flaw detection ability of the laser sensor depends on the angle between the sensor and the surface, the dimensions and the shape of the flaw. A part of the reflected laser light may be blocked and not able to reach the image sensor if the flaw is too deep, shallow or narrow, or of any irregular shape.

5. Conclusions

A laser-based flaw identification system is presented for non-destructive inspection of welds. The laser sensor design is based on the laser triangulation principle and the output is a two-dimensional profile of a target sample, which contains the height and width information of the weld. This two-dimensional profile is then processed by a specially devised algorithm based on the local maxima of the sym8 wavelet coefficients accumulation in order to detect flaws in the vicinity of welds. The positions of flaws on the sample can be calculated to an accuracy of 1 sample point corresponding to 0.12 mm. The experimental results show that the laser-based weld flaw identification system is able to identify and locate ⅓ mm wide surface flaws near the weld cap.

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