Abstract

To ensure the satisfactory performance of a welded structure, the quality of the welds must be determined by adequate testing procedures. During Visual Testing (VT), the weld is examined through the eyes of an inspector to determine surface discontinuities. Although this is commonly considered the easiest, quickest, and least expensive type of inspection, it has some limitations: a certified inspector shall always be on site to perform the test, making it strongly dependant on his experience, knowledge and current environmental conditions. In addition, there is no possibility to record inspection data except standard pictures and comments to be added to inspection reports.

Modern technology brings novel solutions for quality assurance. This article describes a powerful tool which can improve the reliability of VT that combines precise laser measurements, image processing and data cloud computing. A portable magnetic crawler has been developed using a Raspberry Pi SBC, a smart profile sensor and a 5 MPix industrial colour camera in order to gather both weld 3D point cloud and surface pictures. Laser triangulation and processing power directly integrated on board allow an easy weld profile measurement. Undercuts, reinforcement excess, spatters, high-low are precisely detected and sized by the laser sensor while integrated 2D camera records and analyses surface features such contaminations, corrosion, and weld discoloration. The point cloud weld reconstruction is realized stitching together 2D profile data at a fixed interval that can range up to a hundredth of a millimetre with a spatial resolution up to 50um. Inspected weld is fully digitalized in the form of 3D object together with a set of numerical features, data are securely stored in a local flash memory and automatically synchronized with cloud platform for remote data visualization. Automatic weld assessment can also be applied using cloud computing and artificial intelligence (AI) algorithms together with deep learning tools. The combination of images, 3D models, measurements, and other evaluable features all together in the same digital platform definitely enriches the weld assessment making it quicker and reliable with the support of AI, it gives the possibility of remote visual inspection, it ensures a flawless workflow where visual inspection data are stored in a dedicated platform and can be accessed at any moment by stakeholders.

Keywords: Weld visual testing, 3D point cloud, image processing, cloud computing.
1. Introduction

Visual inspection (VT) of weld joint at different stages (before, during, after welding) is an activity carried out by a well experienced inspector which doesn’t require any costly and complex equipment and therefore considered cheap, simple and probably not worth investing time and money on innovating and changing it. However, external factors can impact the on-site evaluation and reporting of inspected welds and it may be difficult to properly re-assess them in the second stage: for example the site is not accessible anymore, or it may be impractical to inspect every weld for large structures or re-inspection may not always be possible due to time or cost constraints.

Figure 1 and Table 1 provide an informative overview of how welds are typically reported in VT, including essential details such as weld data, indication type, measurements, photos and assessment [1]. Once an inspection has been completed, it can become challenging to re-evaluate certain weld features or make corrections to the report. Unfortunately, there may not be an opportunity to measure them again or adjust the report. To address these potential issues and enhance the visual inspection process, it is necessary to explore innovative solutions. Our team has developed a customized magnetic wireless crawler that can collect much more digital information automatically; this device represents a significant advancement over traditional methods and has the potential to transform visual inspection in the field.

2. Enhanced digital weld inspection

2.1 Basic principle

The basic idea is to collect not only flat and static pictures of welds and measurements, but to enable the digitalization of the weld by gathering comprehensive and detailed information which allows to digitalize it. This means merging together surface features, 3D shapes, surrounding attributes in a software that creates an immersive environment for certified inspectors sitting at their desks. There are several different technologies that
can build a true digital representation of a weld, but our team decided to use and combine devices that are well known in industrial and embedded applications, such as a smart laser line profile sensor and an industrial camera both managed in the first prototype by a Raspberry Pi board. The laser sensor uses the triangulation principle for two-dimensional profile detection, in which a laser beam is enlarged to form a static laser line and projected onto the target surface using special lenses. The diffusely reflected light of this laser line is caught by a highly sensitive sensor matrix and a controller calculates the distance information (z-axis) and the position alongside the laser line (x-axis). These measured values are then output in a two-dimensional coordinate system that is fixed with respect to the sensor [2]. While in the past, emitter, detector and controller were 3 different devices, today there are diverse smart profile sensors in the market that perform profile measurements and build a 3D point cloud object representation. Additionally, it has been decided to integrate a 5Mpix industrial colour camera to capture any surface defect, such as discoloration and contamination, or in general any possible anomaly that would require a qualitative assessment. Common communication protocols for cameras are GigE Vision or USB3 Vision, which are the most widely used due to their simplicity. Most PCs and embedded boards are equipped with USB 3 ports and Ethernet ports and their large diffusion has reduced costs and fixed previous device incompatibility. Both standards are based on GenICam [3] which helps to provide consistency for programmers, standardized pixel formats, and better interoperability with other GenICam-based interfaces.

2.2 System description

Our first prototype utilized a Raspberry Pi as the central low-computing system to connect sensors, cameras and structure gathered information. This single board computer based on Linux OS provides necessary modules for onsite operation at a very low cost. Due to limited processing capacity, profile measurements tasks were partially delegated to the smart laser sensor and to a post-processing desktop application, simplifying the mobile software as much as possible. In terms of data acquisition, both the laser profile sensor and the 2D camera are triggered by an encoder embedded in one wheel of the crawler and all the electronical devices are powered using a battery located in a compartment above the rear wheels.

![Figure 2. First weld inspection crawler prototype](image-url)
The crawler is equipped with magnetic wheels that maintain contact with the testing surface, allowing operators to move it forward while monitoring live camera streaming and welding profiles on a 5.5” monitor. All collected data are stored as a first stage in the onboard Raspberry Pi micro-SD card, eliminating the need for additional connected devices. However, they can be easily synced to a cloud storage platform using wireless connectivity on the device. This enables leveraging cloud computing capabilities for demanding and complex quality assurance tasks, ensuring accurate and efficient data analysis.

2.3 Results

With the system shown in paragraph 2.2, inspectors can easily access a collection of 2D and 3D images for each welding point to be examined. The intuitive viewer provides various features, such as zooming, rotating, and sectioning objects, as well as visualizing the 3D point cloud as a coloured height map. This allows inspectors to quickly focus on cap geometry and identify potential shape anomalies.

![Original Weld](image1)

![2D representations](image2)

![3D colored height map](image3)

![Section in correspondence of a non-compliant cap area (Height > 4.0 mm)](image4)

![Cap Height < 4.0 mm (OK)](image5)

Figure 3. Digital weld on a flat surface with cap measurements

The two coloured map images, in both 2D and 3D, clearly depict a red area which indicates an excess of reinforcement. According to ISO 5817 [4] and ISO 6520-1 [5], a smooth transition is necessary and the weld height ($h$) should be $h \leq 1 \text{ mm} + 0.1b$, where $b$ is the weld width. However, in this case, the red area exceeds the specified requirements. By analyzing the acquired 3D data and applying two cross sections in different positions, $h_1$ and $h_2$ were measured to be 4.2 mm and 1.9 mm, respectively. As the weld width ($b$) is 20 mm resulting in $h_{\text{max}}$ 3 mm, it is clear that the first section represents a weld imperfection that is not permitted. Therefore, it is crucial to rectify this defect to ensure the weld meets the required standards.
Undercutting is another common weld imperfection that can occur in welding. In the 3D image it appears as a distinct groove, while in the 2D image, it is visible as a thin, straight line indicating a sharp cut. Cross-sectional views were taken at three different positions along the weld to analyze the extent of the undercutting. One view revealed that the maximum depth of the undercutting (1.09 mm) exceeded the maximum allowable limit according to industry standards [4][5].

2.4 Data analysis and interpretation

The data acquired using the crawler provides valuable information for identifying and analyzing weld imperfections. One of the most promising applications of this data is the use of machine learning (ML) and deep learning (DL) algorithms for automatic anomaly detection. With the rapid advancement of computer vision tools, it is possible to utilize DL algorithms to segment areas of images that significantly deviate from training images. Model training only requires images of samples without defects and, as opposed to other DL methods, no labelling effort is required.
As industry experts, we prioritize for our analysis the use of cutting-edge tools readily available in our environment, such as MVTec Halcon DL.

Anomaly Detection and Global Context Anomaly Detection are the two tools we are using the most, where the model learns common features of images without anomalies. The trained model infers how likely an input image contains only learned features or if the image contains something different. Latter one is interpreted as an anomaly. This inference result is returned as a gray value image. The pixel values therein indicate how likely the corresponding pixels in the input image pixels show an anomaly [6].

Currently, we are actively working on gathering more 2D and 3D weld information to improve the performance of our DL models, with a dedication to advancing the state of the art in this field.

3. Conclusions

The continuous performance improvement of electronic devices and the wide diffusion of smart sensors nowadays allow the acquisition of a huge amount of information, which, if properly managed, enhances any VT assessment. Standard measuring and inspection instruments (i.e., physical gauges) can be complemented by more complex all-in-one devices that acquire, process, store, and share data, optimizing the user (inspector) experience and ensuring data safety, robustness, reliability and an objective interpretation. In this new digital wave, software applications are playing an increasingly key role because of the large amount of data that needs to be managed and presented to the user in a clear and easy-to-interpret manner, as well as the need for modular device integration that should share information and resources. On the other hand, this increasing complexity of physical devices, data management, and user experience needs to match the main scope of a VT, which is to produce comprehensive documentation attesting whether the object under inspection is compliant with its regulations and standards or not. Therefore, one of the most important aspects our team will focus on in the near future is integrating this first prototype with a suitable reporting application.

References

[2] Laser triangulation principles on user manuals of manufacturers of laser triangulation sensors (LMI Technologies, Keyence, Micro-Epsilon)