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Virtual laser vision sensor environment assessment for surface profiling applications

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A B S T R A C T

Due to its potential accuracy and speed, the use of laser vision sensor (LVS) surface profiling systems has been rising at original equipment manufacturer levels in the Oil and Gas industry. The assessment of large structures mandates the deviation from commercially available LVS systems, and the implementation of custom-designed surface profiling capabilities. This effort assesses the use of 3ds Max, a three dimensional (3D) animation software, as a virtual environment to evaluate potential capabilities and limitations of any custom-designed LVS systems. An LVS experimental setup is simulated using the proposed virtual environment. A combination of two known calibration techniques is implemented virtually and experimentally to deliver a calibrated LVS system in both environments. Imported CAD model and its 3D-printed sample as known input profiles are scanned virtually and experimentally, respectively. Scanned data is inverted and compared with the input CAD model to validate the virtual environment for LVS surface profiling applications and preliminarily assess the measurement technique for weld profiling applications. More importantly, this effort facilitates the assessment of custom-designed LVS systems and brings 3D scanning capabilities a step closer towards robust quality control applications in the Oil and Gas industry.

1. Introduction

To increase the fatigue life of drilling and production components, the Oil and Gas community has been raising their design requirements and manufacturing quality control acceptance criteria. Due to its potential accuracy and speed, the demand for LVS applications in the Oil and Gas industry has been growing as part of different quality control processes such as assessing pipe straightness and weld quality. Pipe circularity and straightness are crucial design requirements. If not met, they can adversely affect the critical buckling load a pipe can tolerate, and the quality of welds [1,2]. Different measurement techniques were developed over the years, which ultimately led to the design of a complete real-time vision measurement approach to assess the straightness of large seamless pipes [1]. Since the measurement technique did not utilize advantages offered through the manufacturing process, the procedure required numerous triangulation sensors [2]. This measurement technique was leveraged with the assumption that the pipe rotates about its longitudinal axis [2]. Accordingly, pipe straightness can be assessed through measuring its eccentricity using the upper-tangent point from the data fit to a circle. Following this assumption further reduced the number of triangulation sensors to two LVS measurement heads each consisting of a relatively high-speed video camera, and a laser source placed at a fixed position relative to the camera.

Recent improvements in welding technologies have been leaning more towards robust automated welding processes. This mandates real-time seam positioning and tracking during the welding process. LVS technical capabilities are considered suitable for this application as long as the optical capabilities are not affected by the welding arc during the welding process [3]. To minimize the arc interference with the reflected laser wavelength, a suitable narrow-band optical filter can be added to the LVS measurement system [3]. Furthermore, the feasibility of using straight [3,4] and circular [5] laser trajectories has been proven feasible for real-time seam position tracking during the welding process with implementing the right LVS system calibration technique and digital image processing algorithms. Further development of real-time LVS measurement feedback demonstrated its feasibility to deliver clad height requirements during laser deposition processes [6].

As part of post-weld inspection processes, the Oil and Gas industry has been raising their requirements to implement reliable metrology methods to assess a weld's profile before and after grinding. This is to guarantee that the weld cap height does not exceed the design requirements nor does the material lost from the grinding process violate the minimum wall thickness requirements around the weld. This

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explicitly dictates surface measurements around the weld and renders the numerous weld surface measurements using solid gauges impractical for post-weld quality control since they only offer discrete measurements along the weld. Automated LVS measurement capabilities have demonstrated a strong potential to meet these rising demands and deliver the coverage needed along the weld based on simple laser triangulation principles [7–10]. Implementing a simple calibration technique established LVS measurement potential in assessing welds surface profiles [7]. This calibration approach treats the LVS system as a black box where system calibration is implemented at controlled stand-off distances, which is the distance between the LVS and the surface of interest. Using wavelet transforms extended LVS surface profiling potentials through detecting artificially placed surface flaws [8]. In both cases, the calibration approach was not tested for dimensional accuracy relative to known input weld profiles. This, along with system calibration at controlled stand-off distances, hindered the introduction of this technology at original equipment manufacturers (OEMs) levels in the Oil and Gas industry where custom-designed LVS surface profiling systems are the potential solution to surface profile features in large structures.

It can be clearly stated that welds in the Oil and Gas industry deviate from the smooth axisymmetric computer-aided design (CAD) models used in the fabrication of their welded products. In other words, welds do not have CAD models representing their actual profiles. Therefore, it becomes rather difficult to accurately assess the life of a welded product without importing the actual weld profile into their finite element simulation packages for stress concentration factors and fatigue analyses. Moreover, existing weld CAD models cannot be used as a reference to assess the accuracy of custom-designed LVS surface profiling capabilities.

This effort assesses the use of 3ds Max, a three dimensional (3D) animation software, as a virtual environment to evaluate potential capabilities and limitations of any custom-designed LVS systems. A combination of two known calibration techniques is implemented virtually and experimentally to deliver a calibrated LVS system in both environments. Imported CAD model and its 3D-printed sample as known input profiles are scanned virtually and experimentally, respectively. Scanned data is inverted and compared with the input CAD model to validate the virtual environment for LVS surface profiling applications and preliminarily assess the measurement technique for weld profiling applications. More importantly, this effort facilitates the assessment of custom-designed LVS systems and brings 3D scanning capabilities a step closer towards robust quality control applications in the Oil and Gas industry. It is worth mentioning here that the intent of this effort is not to develop a new calibration technique nor a new laser stripe peak detection algorithm. It is rather the use of existing techniques to validate the use of the virtual environment and 3D-printed profiles for LVS surface profiling applications. If proven feasible, the virtual environment can ultimately be used to develop and evaluate LVS system calibration and measurement techniques prior to any physical implementation whether the system is custom-designed and assembled or acquired from readily available products in the market.

2. LVS surface profiling system

It is crucial to deliver a simple yet practical LVS system with robust and accurate calibration process to bring 3D computer vision closer to a manufacturing environment. LVS systems consist of three main components, namely a charge-coupled device (CCD) camera, a laser-line projector, and an encoded scanning mechanism to invert data from the camera coordinate system to a randomly selected world coordinate system. Fig. 1 illustrates a schematic representation of an LVS system relative to (a) a randomly selected world coordinates and (b) the image frame as captured within the camera field of view (FOV). In this schematic representation, the laser-line projector is placed in a fixed position relative to the camera used in the LVS system. In compliance with the pinhole approximation, laser stripe or laser-line projection must be positioned at a distance relatively far from the camera in comparison to its lens focal length and certainly within the camera FOV. Scanning parts of rather complicated features mandates checking for occlusion during or prior to the scanning process. For automated laser scanning applications, CAD path planning is a good practice that allows checking for optical constraints such as FOV, occlusion and depth of field (DOF) [11,12]. Based on the sample designed for this study, no occlusion problems were detected since the entire laser stripe was visible within the camera FOV throughout the entire scan. Further improvement can be delivered through evaluating the part prior to conducting the inspection to analyze for the density, completeness and accuracy of the measurement to have an optimal scanning trajectory from a metrological prospective [13].

As shown in Fig. 1, laser-line projection follows the surface profile of interest. Encoded recording of laser displacements along the scanning direction delivers plenty of 3D information. However, since these displacements are captured in the image frame used in the LVS system, a proper system calibration is required to take data points captured in the image frame to points in the randomly selected world frame of reference Fig. 2 illustrates the plan used in this study to validate the virtual environment capabilities for LVS surface profiling applications. To replicate the experimental setup in the virtual environment, camera specifications, checkerboard dimensions, laser-line projector, sample CAD model, and the scanplan used in the real experimental setup are simulated in 3ds Max. A combination of two known calibration techniques is virtually implemented to calibrate the camera and the laser plane position relative to the camera to have a calibrated LVS system. Based on the sample CAD model, a scanplan is generated to simulate the actual scanplan in the experimental setup. Once the sample CAD model is scanned using the virtually calibrated LVS system, inversion algorithm is implemented on recorded or rendered data to get the virtually measured surface profile of the input CAD model. To illustrate the capability of the simulated LVS system, the virtually measured surface profile is subtracted from the input surface profile of the CAD sample. The deviation from the CAD model illustrates the potential capability the actual experimental setup can reach. From the experimental side of this study, the CAD model is 3D-printed to have a known input surface profile to be measured after calibrating the LVS system. The experimentally measured surface profile of the 3D-printed sample will be subtracted from the CAD model surface profile. This deviation will be compared to the deviation obtained from the simulation environment to better assess the experimental setup capabilities and limitations.

3. LVS system calibration

LVS surface profiling lends itself for weld quality assessment [7,8]. The use of laser triangulation method offers a simplified LVS system calibration where the camera and laser plane are calibrated as a black box [7]. Even though the method illustrated a strong potential towards mapping welds surface profiles, the accuracy of this technique was not compared relative to known input profiles. Moreover, the technique is rather sensitive to stand-off distances. If left uncorrected, the calibration can introduce a ± 0.5 mm variation in assessing the actual surface profile. To compensate for this lift-off sensitivity, calibration has to be implemented at controlled stand-off distances over the calibration block. Using custom-designed LVS system around large structures requires frequent movement of the LVS system and can easily bring the LVS system out of calibration. Unfortunately, calibrating the system at controlled stand-off distances does not offer a practical solution is such a rough environment. These reasons hindered the introduction of this technology in the Oil and Gas industry. Following the black box calibration approach, a feasibility analysis demonstrated wavelet transforms potentials toward detecting artificial surface defects that are as small as 1/3 mm in width [8].

In this effort, a different LVS system calibration technique that