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Simple laser vision sensor calibration for surface profiling applications

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ABSTRACT

Due to the relatively large structures in the Oil and Gas industry, original equipment manufacturers (OEMs) have been implementing custom-designed laser vision sensor (LVS) surface profiling systems as part of quality control in their manufacturing processes. The rough manufacturing environment and the continuous movement and misalignment of these custom-designed tools adversely affect the accuracy of laser-based vision surface profiling applications. Accordingly, Oil and Gas businesses have been raising the demand from the OEMs to implement practical and robust LVS calibration techniques prior to running any visual inspections. This effort introduces an LVS calibration technique representing a simplified version of two known calibration techniques, which are commonly implemented to obtain a calibrated LVS system for surface profiling applications. Both calibration techniques are implemented virtually and experimentally to scan simulated and three-dimensional (3D) printed features of known profiles, respectively. Scanned data is transformed from the camera frame to points in the world coordinate system and compared with the input profiles to validate the introduced calibration technique capability against the more complex approach and preliminarily assess the measurement technique for weld profiling applications. Moreover, the sensitivity to stand-off distances is analyzed to illustrate the practicality of the presented technique.

1. Introduction

The Oil and Gas community has been tightening their design requirements and corresponding acceptance criteria to increase the fatigue life of different drilling and production components. Due to its potential accuracy and speed, laser vision sensor (LVS) applications in the Oil and Gas industry have been progressively growing as part of quality control of different manufacturing processes. Assessing pipe straightness and circularity are crucial elements to fulfill design requirements. If not met, they can adversely affect the critical buckling load a pipe can tolerate and the quality of seam and circumferential welds [1,2]. To assess the straightness of large seamless pipe structures, the feasibility of laser triangulation measurement technique was tested and ultimately led to the development of a complete real-time laser-based vision measurement system [1]. In this study, the elliptical fitting of laser-line projection was described through a general conic equation to estimate the center of the cross-sectional profile. The deviation of these center points along the axis of the pipe were used to assess the pipe straightness. Unfortunately, the technique was not very practical since it did not leverage advantages nor account for errors related to the manufacturing process itself [2]. For these reasons, the technique mandated numerous triangulations sensors as part of system design [1]. To overcome these obstacles, the technique capability was enhanced with the assumption that the pipe rotates about its longitudinal axis [2]. With this assumption, pipe straightness was assessed through monitoring the movement at the end of the pipe with circular fitting of cross-sectional data where tangent points are used to estimate the pipe eccentricity. This assumption not only allowed relating the pipe eccentricity to its straightness, but also reduced the number of triangulation sensors to two LVS heads.

Fulfilling pipe straightness and circularity, as design requirements, are crucial parameters to enhance the quality of welds. Further improvement can be attained through automating the welding processes and making it more robust through reducing the human interference. This mandates real-time seam positioning and tracking, where LVS measurement systems provide a suitable feedback to automate the welding processes. Since the feedback accuracy counts on a vision-based sensor, it is crucial to design LVS systems that are not influenced by the welding arc generated during the welding process [3]. Adding a suitable narrow-band optical filter, which only passes the laser wavelength, has been proved feasible to minimize the arc light interference with the LVS system capability in seam positioning and tracking [3]. Other than the use of optical filters, the implementation of suitable digital image processing filters and integrating them as part of LVS system calibration techniques help reduce the arc light interference

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with laser-stripe peak detection [3–5]. Implementing these techniques, and the use of straight [3,4] and circular [5] laser projections demonstrated LVS system capabilities to properly assess the seam position and tracking during welding processes. Moreover, these techniques were leveraged to deliver real-time feedback to support laser deposition processes and provide controlled clad heights [6].

To automate the visual inspection process over welds in a manufacturing environment, LVS surface profiling capabilities have been illustrated based on simple laser triangulation principles [7,8]. A black-box system calibration approach was implemented at controlled stand-off distances [7], i.e., the distance between the vision sensor and the surface of interest. The black-box approach used the simple principle of laser triangulation and compensated for measurement errors through assessing a rectangular calibration block's width and depth at controlled stand-off distances. This demonstrated the LVS system potential in assessing the surface profiles of welds without the need of measuring the camera intrinsic and extrinsic parameters nor defining the laser plane. The method illustrated a strong potential towards mapping welded surface profiles. However, it was not tested for dimensional accuracy against known input profiles. Moreover, the calibration method is rather sensitive to stand-off distances. If left uncorrected, it can introduce a ± 0.5 mm error in assessing the actual surface profile. Accordingly, the technique mandates calibrating the LVS system at controlled stand-off distances which makes the technique less practical to be applied in a manufacturing environment.

The proper definition of a laser plane in a world coordinate system using a calibrated camera is a crucial element to overcome the measurement sensitivity to stand-off distances. Different methodologies have been introduced in the literature. A technique was developed using at least six world lines, where the use of laser-line projection on a defined world line and the corresponding point of intersection in the image frame can be utilized to define the laser plane relative to the world coordinate system [9]. This approach was later leveraged over the use of at least six defined world planes [10]. Alternatively, the use of two or three orthogonal planes can be used to define the laser plane following the cross-ratio invariance to generate the world points on a laser plane [11,12]. This approach requires a rather expensive calibration setup that allows simultaneous capturing of calibration images to view the orthogonal planes of the calibration object. A co-called "standard ruler" calibration technique can be used as well to define the laser plane by mounting the calibrating object or plane on a well-controlled linear translational axis to get different laser-line projections along the axis [13,14]. The later approach is inconvenient from an operational point of view as it is considered time consuming during the calibration process and requires high accuracy in moving the object along the axis. The rising demand to develop robust and practical calibration of structured light led to the development of a simple technique that counts on viewing a planar object at, at least, two random orientations using the invariance cross-ratios to determine the world points on a laser plane using a calibrated camera [15]. The later technique is used in this study and explained in more details in the calibration section.

This effort introduces an LVS system calibration technique representing a simplified and combined version of two known and relatively more complex calibration techniques [15,16], namely used for camera and laser-plane calibrations. The new calibration technique captures the camera and laser-plane parameters needed in a single image without the need to calibrate the system at controlled stand-off distances. Recently, Autodesk 3ds Max demonstrated its capability as a commercially available virtual environment that lends itself for developing and evaluating LVS calibration and measurement techniques [17]. Along with the experimental work in the present paper, the virtual environment is used to evaluate the simple calibration technique. Both, the simple and the more complex calibration techniques are implemented virtually and experimentally to scan simulated and three-dimensional (3D) printed features of known profiles, respectively. Scanned data is transformed from the camera frame to points in the world coordinate system and compared with the input profiles to validate the introduced calibration technique capability against the more complex approach and preliminarily assess the measurement technique for weld profiling applications. Moreover, the negligible sensitivity to stand-off distances is analyzed to illustrate the practicality and robustness of the presented technique within the dynamic range of interest.

2. LVS surface profiling system

It is crucial to provide an LVS surface profiler system with a robust and yet accurate calibration process to bring 3D computer vision a step closer to a manufacturing environment. As shown in Fig. 1, the LVS scanner consists of a charge-coupled device (CCD) camera, a laser-line projector, and a scanning platform. This allows a random sample to be scanned for 3D surface profiling applications. This schematic representation shows the LVS system relative to (a) an arbitrary world frame of reference and (b) the image frame of reference as captured within the camera field of view (FOV). In this study, the laser-line projector is placed in a position and an orientation fixed relative to the camera frame of reference, where the laser plane is defined following the complex and the proposed simple calibration techniques. Following the pinhole approximation, the laser-line projection has to be at a distance

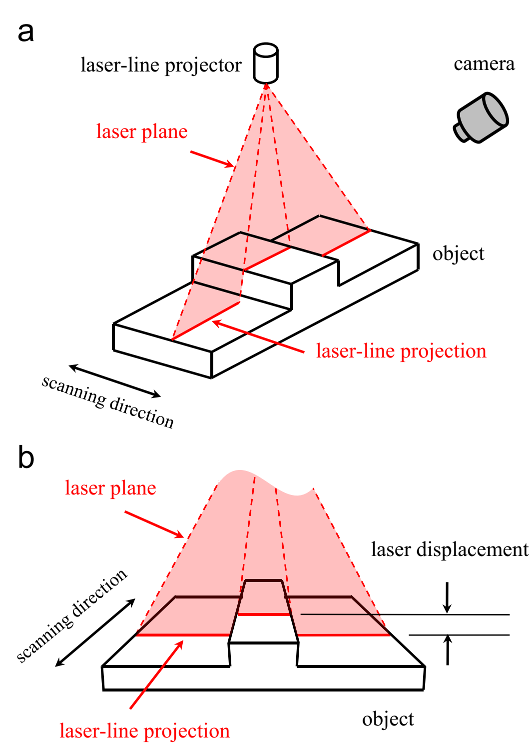

Fig. 1. A schematic representation of an LVS system setup relative to (a) arbitrary world and (b) image frame coordinate systems.