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LIDAR-based Automated 3D Inspection System for Corrugated Surface Defects

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With the advantages of high stiffness and long durability, corrugated surface structure is widely employed in the manufacturing, construction, and transportation areas. Most corrugated surfaces are deployed outdoors and exposed to external crushes and weather changes. To improve operating performance and reduce maintenance efforts, an effective and efficient defect inspection system is of great importance. However, the varying size and shape of corrugated surfaces challenge the human inspection process leading to low flexibility and efficiency. Besides, uncontrolled environmental lighting and weather condition burden the adoption of traditional imaging cameras. To address the demanding inspection requirement for corrugated surface defects, this work develops a laser imaging, detection, and ranging (LIDAR)-based automated 3D inspection system. The system is composed of an online LIDAR scanning platform and defect inspection algorithm. By virtue of infrared light pulses in LIDAR, the scanning process and results are not affected by environmental lighting variations. The scanning platform is designed to capture only one shot for the surface's short edge and continues scanning along the long direction. Under this scanning mode, the wide field of view and near filed accuracy of LIDAR are fully utilized. The fine and densely grained morphology information along the surface's short edge can be rapidly formulated in the 3D point-cloud view. The complete 3D point cloud is then automatically analyzed by a four-sequential stage algorithm: cloud transformation, plane simulation, abnormality clustering, location and area determination. The point cloud range is filtered and calibrated to identify and transform the corrugated surface with its back bottom corner as the origin. Through the iteration of random sample consensus, an approximate plane is simulated to segment normal and abnormal points. The Euclidean distance is adopted for abnormality clustering to mesh abnormal points according to their neighbouring intervals. 3D bounding boxes are generated for the abnormal clusters. The centroid and area of the bounding boxes are found to quantify the defect location and dimension. The proposed LIDAR-based defect inspection system and algorithm have been evaluated in the inspection of defects like dents and deformation for manufacturing corrugated surface structures.

NOMENCLATURE

3D = *three dimensional*
LIDAR = *laser imaging, detection, and ranging*

1. Introduction

In 1829, the first patent for the corrugated metallic sheet was invented by London Dock Company [1]. Through its linear ridged structure, the bending strength of a corrugated surface object is enhanced. From buildings to logistics, it is common to see corrugated surface structure applications. In logistical transportation, corrugated containers are widely used for shipping products and materials. Mediterranean Shipping Company [2] and Maersk [3] are the two largest shipping companies, which own large amounts of twenty-foot equivalent units. With the protection of corrugated surface structures on sides and roofs, shipping containers can endure various travelling modes.

Despite the rigidity and strength of the corrugated surface structure, corrugated objects could still suffer damage caused by operating uncertainties. According to the technical reference from Singapore Standards Council [4], Code D and Code C are two condition codes for the description of container equipment status. Code D includes dent, bent, and frame or structure bowed. In the meantime, Code C indicates crack, cut, hole and broken parts. As those damages might directly affect the proper quality of corrugated surfaces, effective and efficient inspection is of great importance for stable usage.

Currently, the main inspection approach for corrugated surface defects relies on human vision. Subjective assessment and experience differences might lead to the result variance. Besides, inspectors must search around the surface and mark potential damages one by one. The time-consuming burden is notable during the whole process [5]. In addition, most existing inspection systems for corrugated surfaces are based on images [6], which easily suffer from variations in weather conditions, surface sizes, and object movement.

To address these concerns for corrugated surface defect identification, a LIDAR-based automated 3D inspection system is proposed in this work. Through the design of a LIDAR scanning platform and defect inspection algorithm, the proposed system is capable to provide reliable and online inspection service for the maintenance of corrugated surface objects.

2. LIDAR-based Automated 3D Inspection System

2.1 LIDAR Scanning Platform

The detailed organization of the proposed LIDAR-based automated 3D inspection system is presented in Fig. 1. From hardware, software and integration levels, a complete inspection scheme is developed.

The container sides are taken as examples of corrugated surface instances. At the hardware level, a LIDAR scanning platform is established. Because infrared light pulses in LIDAR are not affected by external lighting conditions, two LIDAR devices are responsible for the sidewall inspection and are allocated on both sides of the container in Fig. 2 (a).

To guarantee effective scanning with only one shot, the view angle of LIDAR devices is perpendicular to the surface's moving direction in Fig. 2(b). Thanks to the wide LIDAR view field and near-field accuracy, the short edge only needs one shot. The long edge shape can be then automatically formulated during the surface movement.

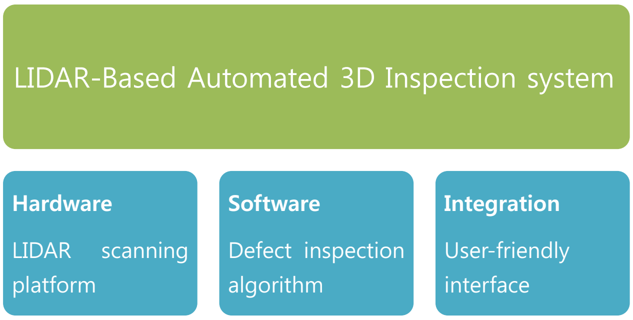

Fig. 1 Proposed inspection system structure.

(a) LIDAR scanning platform (b) Position relationship
Fig. 2 LIDAR scanning platform and position relationship.

2.2 Defect Inspection Algorithm

As an online platform, our designed LIDAR scanning platform is capable to provide detailed surface morphology information via 3D point cloud in the second level.

To identify the surface defects, a four-sequential stage inspection algorithm is built into this system. As shown in Fig. 3, the whole analysis workflow is organized into four stages of cloud transformation, plane simulation, abnormality clustering, location and area determination.

In Stage I of cloud transformation, the point cloud range is filtered along the X-Y-Z direction. On account of the surface continuity, the largest cluster from the whole 3D point cloud is extracted reducing scanning noises and data range. After that, the corrugated 3D point cloud is transformed to make its bottom corner the origin.

Since deformation and dent are the main defects for a corrugated surface, a middle plane averaging the corrugated surface peaks and valleys is generated by random sample consensus iteration [7] to distinguish between normal and abnormal points. This consensus iteration gradually enlarges the compatible points by adjusting the four parameters a, b, c, d of plane P:

$$P: ax + by + cz = d \quad (1)$$

Stage II of plane simulation then outputs abnormal points through the following range criterion:

$$S_{abnormal} = \{(x, y, z) | \|ax + by + cz - d\|_2 > \varepsilon\} \quad (2)$$

where ε indicates the tolerance range.

After that, $S_{abnormal}$ is integrated based on neighboring Euclidean distances in Stage III of abnormality clustering.

In Stage IV of location and area determinations, eight points of bounding boxes are generated along 3D coordinate system directions. The centroid and area of bounding boxes are then determined to specify the defect position and size.

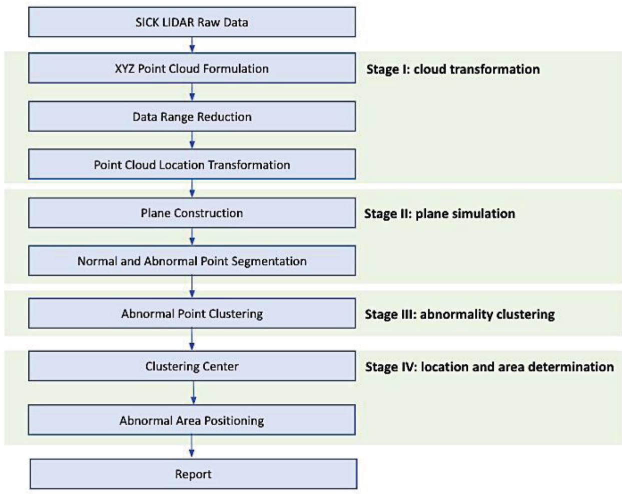

Fig. 3 Defect inspection algorithm workflow.

2.3 Integration

For convenient interaction with end users, a friendly user interface is also developed to allow online monitoring and detection. In the Manual Control part of Fig. 4, "Start Scan" and "Stop Scan" buttons are used to control the LIDAR scan interval. After the scanning, the visualization and inspection modules are triggered by "Point Cloud" and "Detect" buttons. In the meantime, inspectors can also utilize "Load" function to analyze historical data.

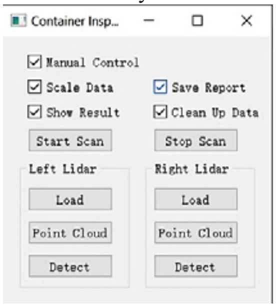

Fig. 4 User-friendly interface.

3. Experimental Results

3.1 3D Point Preprocessing Test

Data preprocessing is the prerequisite for defect inspection, which is achieved in Stage I. To verify the benefit of this stage, Fig. 5 and Fig. 6 show the 3D point clouds before and after Stage I. In Fig. 5, numerous environmental data surround the corrugated surface. With the help of Stage I, most environment data are removed from the 3D view.

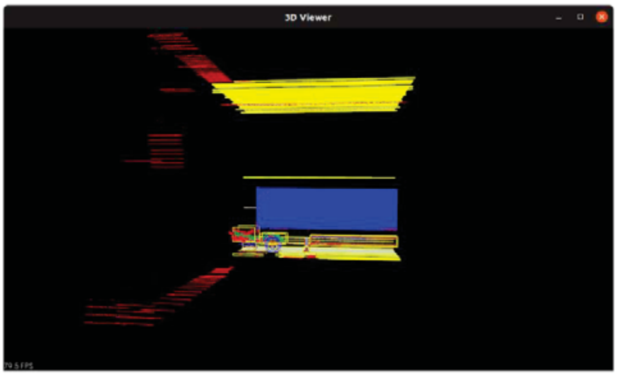

Fig. 5 LIDAR Raw data.

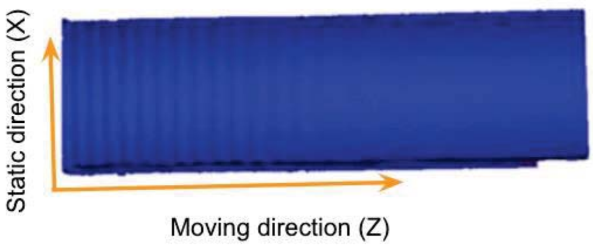

Fig. 6 3D point cloud after Stage I.

3.2 Positioning Accuracy Test

After the preprocessing stage, a plastic stick is placed on a moving container surface to test the localization capability of the proposed LIDAR-based automated 3D inspection system in Fig. 7. Based on the defect inspection algorithm, those abnormal points are accurately highlighted in Fig. 8, which verifies the system effectiveness.

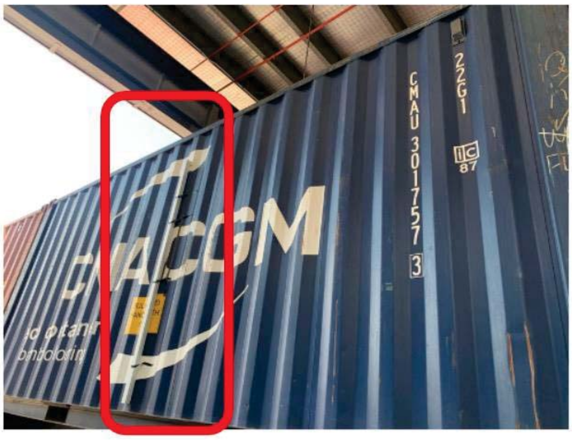

Fig. 7 Positioning experiment setup.

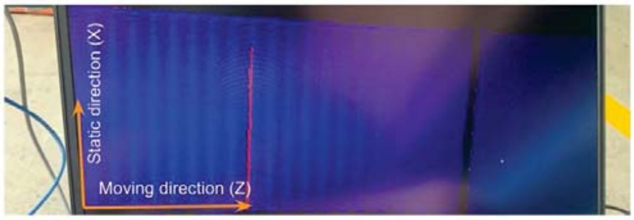

Fig. 8 Online inspection results.

3.3 Abnormality Inspection Test

In addition to the positioning test, abnormality inspection tests are implemented to investigate the surface abnormality. An example is presented in Fig. 9 with a dent on the corrugated surface.

The inspection result is provided in Fig. 10 with the location information in Table 1. It can be seen from Fig. 10 and Table 1 that the developed algorithm is able to identify this decent area and automatically generate the location information. The whole process is finished in 13.26 seconds on a laptop of CPU i7-10750H, which shows the efficiency advantage of the proposed system.

Fig. 9 Abnormal dent on corrugated surface.

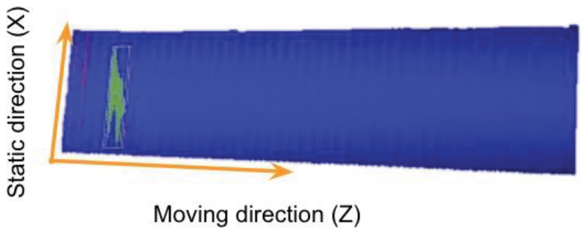

Fig. 10 Dent inspection result.

Table 1 Dent inspection location.

Z_{min}	1164.89 mm
Z_{max}	1302.39 mm
X_{min}	429.04 mm
X_{max}	2104.51 mm

4. Conclusions

A LIDAR-based automated 3D inspection system is developed for the defect examination of manufacturing corrugated surface structures. By designing the LIDAR scanning platform, the complete 3D point cloud view for a moving corrugated surface can be extracted without stopping the object. A four-stage algorithm is then proposed to filter environmental noises and locate the surface abnormality. With a concise user-friendly interface, the online visualization and detection functions are easily controlled by inspectors. From three experimental aspects of 3D point preprocessing, positioning accuracy, and abnormality inspection, the effectiveness and efficiency of the proposed system are fully demonstrated.

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