A Tactile Sensor Roller for In-Process Inspection of Composites

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***Abstract*— We design a tactile sensor roller for detecting defects on composites in process to improve inspection efficiency and automation. It obtains depth information of defects through the deformation of the painted gel elastomer and classic photometric stereo whilst monitoring rolling speed and consolidation force of the inspection process. We inspect a $35\ cm \times 18\ cm \times 0.5\ mm$ woven prepreg at three speeds and use three metrics to assess and compare the reconstructed images of the defects. We find that the depth maps at the three speeds have similar depth consistency, and the angular standard deviation and entropy of the normal map and albedo map at the high speed ($47.83\ mm/s$) are 22.52% and 51.48% lower than those at the low speed ($11.73\ mm/s$), respectively.**

I. Introduction

Although non-destructive testing (NDT) like ultrasonic testing (UT) and infrared thermography dominates quality control of composites [1], they are for post-manufacturing quality assurance only. A laser line scan sensor (LLSS), an in-process inspection tool is sensitive to surface properties of the composites, such as reflectivity, colour and texture. [2].

It is not the first time that tactile perception has been applied for quality assurance. Elkington et al. [3] proposed a method using nearest neighbour method to compare differences in pin positions of the TacTip [4] to identify defects in the ply during lay-up. Experimental results show that TacTip is able to detect not only defects on flat composites, but also fractured with a width of 3.18 *mm* in automated fibre placement (AFP). TacTip has also been applied to check alignment gaps in automotive components with a width of 0.35 *mm* by Lepora et al. [5]. They achieved active sensing for TacTip using Bayes' theorem based on the analysis of active sensing sequences. However, TacTip has low inspection efficiency due to small perceptual area. In Lepora and Ward-Cherrier's study [5], TacTip took 750 *ms* per click, which means it takes 110 clicks to evaluate one gap, or 82.5 *s*.

TouchRoller proposed by Cao et al. [6] addresses the issue of perceptual efficiency. Its cylindrical shape keeps it in contact with the detected surface throughout the rolling movement, thus continuously collecting tactile sensations. TouchRoller takes 10 seconds to cover the area that GelSight takes 196 seconds to cover [7]. However, TouchRoller failed to acquire depth information on the inspected surface. Therefore, we arrange three LED beads with different angles of incidence, allowing the acquisition of depth information through photometric stereo.

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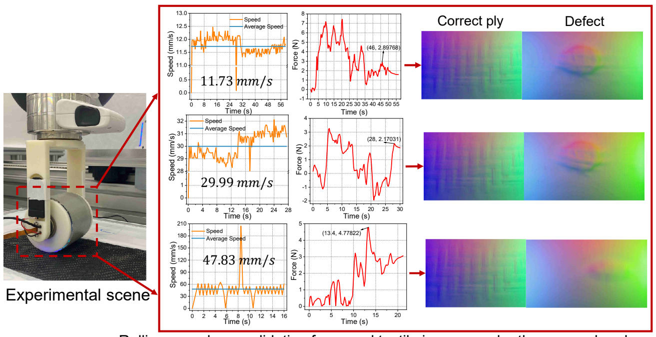

Rolling speed, consolidation force and tactile images under three speeds, where the time point and force value at which the defect is detected are labelled.

Fig. 1: Illustration of the tactile sensor roller detecting composites. The right side shows the collected data containing tactile images, rolling speed and consolidation force. Different speeds and contact forces affecting the image quality can be observed.

To address the dilemma, we propose a vision-based tactile sensor roller for detecting defects on composites in process as shown in Fig. 1. It contains a camera, internal light sources, a speed sensor, a force sensor, an acrylic tube and a painted gel elastomer insulates external light. As it rolls over the defect, the elastomer deforms and causes a change in light and shadow, which is captured by the camera as an input to photometric stereo for 3D reconstruction while the speed and force sensors monitor the rolling speed and consolidation force of the inspection process.

II. Method

A. Hardware Design

The internal structure of the tactile sensor roller is shown in Fig. 2. It is a cylinder with a diameter of 73 *mm* and a height of 73.5 *mm*. The connecting tab is located in the centre. The camera is pressed down by the top connector to film the contact area. The bottom connector is mounted below the force sensor and connects to an $M10$ wheel on its right side to transfer force. The red, green and blue LED beads are affixed to the lower edge of the connecting tab to provide internal illumination. A fixed camera position, a Lambertian surface and three point light sources enable the tactile sensor

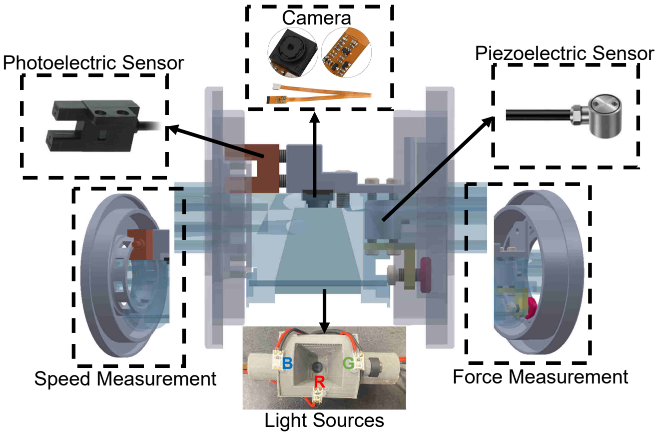

Fig. 2: Internal structure of the tactile sensor roller.

roller to acquire depth information of the defects via classical photometric stereo [8]. The manufacturing cost of one of the tactile sensor rollers is *GBP* 58.34, excluding chemicals and consumables for 3D printing. It has a total of 20 parts, of which 7 are 3D printed and 13 are outsourced.

B. Software

We measure the rolling speed dividing the length of the gap on the left wheel by the duration of the light from the photoelectric sensor is blocked or passed. We use a piezoelectric sensor to measure consolidation force. It converts mechanical stress into electrical output. As shown in Fig. 3, we begin by adjusting the light intensity of the three light sources to balance the colours of the image captured by the camera. Then we separate the blue, green, and red channels of the image while preserving the original dimension. These three images, a mask image and a light matrix obtained by light calibration serve as inputs to classical photometric stereo. The output is a normal map, an albedo map and a depth map, where the depth map is a greyscale image that indicates the relative vertical distance from the camera.

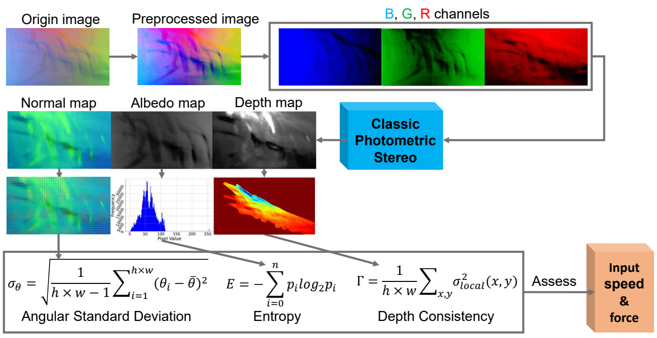

Fig. 3: Flow of image processing and evaluating. Input the blue, green, and red channels of the preprocessed image, and the classical photometric stereo output a normal map, an albedo map, and a depth map, which are quantified into three metrics: angular standard deviation, entropy and depth consistency to assess the speed and force corresponding to the origin image.

III. Experiment

We place a piece of 35 $cm \times 18$ $cm \times 0.5$ mm woven prepreg and set a foreign object and wrinkles at two spots underneath it as shown in Fig. 1. Franka Emika Panda robot controls the tactile sensor roller to start at one corner of the woven prepreg, roll forward to the other end, and roll back from the other end to complete the exploration.

We use a weighted score of the three metrics to assess the speed and force corresponding to the input image, i.e., angular standard deviation (ASD) of surface normals for the normal map, entropy to assess the information richness of the albedo map and global average local variance (GALV) to assess the consistency of the depth map (Fig. 3). The larger the value of the metric, the higher the score since it means that the reconstructed image retains more texture information of the inspected surface. ASD and entropy are weighted at 40%, and GALV is weighted at 20%.

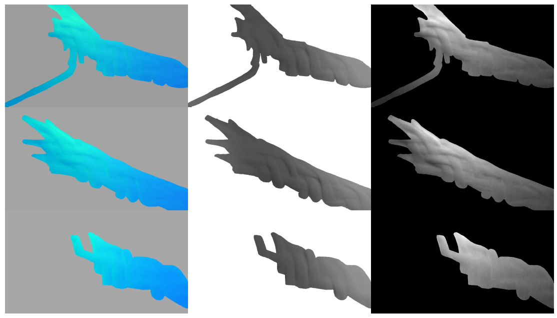

Fig. 4: Reconstructed images of the defect and at three speeds (11.73 mm/s, 29.99 mm/s and 47.83 mm/s), from left to right are the tactile image, normal map, albedo map and depth map.

TABLE I: Assessment of reconstructed images at three speeds with weighted scores.

	ASD 40%	Entropy 40%	GALV 20%	Weighted Score
Low Speed	18.69352	2.69512	106.34231	29.82
Medium Speed	15.52589	2.02573	107.75187	28.57
High Speed	14.48413	1.30771	106.61208	27.64

IV. Result

The tactile images and 3D reconstructed images captured at three speeds are shown in Fig. 4. We find that the angular standard deviation and entropy at the high speed (47.83 mm/s) are 22.52% and 51.48% lower than those at the low speed, respectively, as shown in TABLE I. Image reconstruction at the low speed performs best under this scoring system, 4.39% and 7.90% higher than those at the medium and high speeds, respectively.

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