In: 2024 IEEE International Conference on Industrial Technology (ICIT), 25-27 March 2024 Bristol, UK
DOI:10.1109/ICIT58233.2024.10540981

An Innovative Tactile Sensor Roller for Composites Inspection

Zhenyu Lu*
Bristol Robotics Laboratory,
University of the West of England
Bristol, UK
zhenyu.lu@uwe.ac.uk

Xiaolong Li*
Bristol Robotics Laboratory,
University of the West of England
Bristol, UK
xiaolong2.li@live.uwe.ac.uk

Tunwu Li*
Bristol Robotics Laboratory,
University of the Bristol
Bristol, UK
fn22216@bristol.ac.uk

Xiaodong Xu
Centre for Aeronautics, School of Aerospace, Transport and Manufacturing,
University of Cranfield
Cranfield, UK
xiaodong.xu@cranfield.ac.uk

Chenguang Yang⁺
Bristol Robotics Laboratory,
University of the West of England
Bristol, UK
Cyang@ieee.org

***Abstract*—A vision-based tactile sensor roller prototype has been designed and developed to detect defects on composite prepreg and dry fabric surfaces. The tactile sensor features an innovative design comprising a transparent acrylic tube encased in a gel elastomer. The outer tube serves as a protective and flexible layer, while the inner structure includes a connecting shaft equipped with a camera, force, and speed sensors. This configuration allows for detailed capture of tactile information, integrating visual and pressure data for comprehensive sensory feedback. The connecting shafts are fitted with wheels and handles at both ends, enabling human manipulation and control. Typical defects such as wrinkles, gaps, overlaps and foreign objects and debris (FOD) can be detected by this prototype. In this study, we assessed the performance of the tactile sensor roller by rolling it across areas affected by human-made composite prepreg and dry fabric defects that include wrinkles and foreign objects. With the comparison of the tactile image results, we have demonstrated that the tactile sensor roller can identify flaws with a precision of 0.125mm. It can efficiently examine a 35cm by 18cm section of woven fabric without compromising the integrity of the 3D data gathered. This innovative tactile sensor is set to enhance the automation of the hand layup process. It enables real-time quality control, substantially reducing the need for extensive manual inspections. This leads to a significant cut in inspection costs, making the manufacturing process both more efficient and cost-effective.**

Keywords—Tactile sensor, Composites layup, Manufacturing, Defect inspection

I. INTRODUCTION

Composites play a crucial role in elevating the efficiency of components, finding extensive applications in industries like automotive and wind power. With rising demand, the production of composites is also on the upswing. Prepreg composites offer numerous benefits, including a remarkable stiffness-to-weight ratio and exceptional fatigue resistance when compared to conventional materials [1].

Hand layup serves as a primary process in composites moulding, particularly for prepreg based composites. This procedure involves cutting, laminating, and polymerization. Despite its prevalence, the method incurs high production costs and low productivity due to its limited automation. However, it is due to the human operator's participation, that the composites prepregs placement accuracy can be ensured while preventing the manufacturing defects through tactile feedback. The capability of adapting operations in real-time through tactile feedback enables operators to promptly correct deviations as they arise [1]. The complexities of this closed-loop control mechanism underscore the challenging nature of automating the hand layup process.[1] The main challenge in hand layup process lies in the demand for a high level of coordinated perception, motion, and judgment [2]. For example, operators use visual and tactile senses to perceive the composites ply, employ hand dexterity to drape it and assess the ply's quality [3]. Meanwhile, the majority of automated processes undergo quality checks only after the plies have been laid, a step that is also manually carried out by operators.

Throughout the existing vision-based composites inspection technology, it is not difficult to find that there are many problems in the inspection process. For example, ultrasound inspection requires media and special equipment; infrared radiation thermography needs a heat source for visualization; The vision-based laser inspection system, while effective for surface quality control of composites materials during the process, leads to significant equipment expenses, with the cost of one laser inspection solution exceeding 20 thousand dollars. [4]. In response to this challenge, we have developed a solution: an optical tactile sensor designed in a roller shape integrated with a force and speed sensor. This roller, attachable to the end of the robot arm, is designed to simulate and visualise the real-time human hand sensory feedback that operators receive during the hand layup process. By leveraging the gathered feedback, the robot is capable of assessing the ply quality and independently adjusting layup numbers like force, speed, and direction. The implementation of this tactile roller facilitates real-time defect detection in the composites layup process, leading to reduced process cycle times and enhanced production efficiency. In addition, the above technique checks the quality after the layer is laid. The ply-by-ply check delays the manufacture of the parts and even accounts for more than 50% of the entire automatic fibre placement (AFP) time [1].

The tactile sensor, based on a reflective membrane, exemplifies a high spatial resolution tactile image sensor [5]. The primary advantage of the reflective membrane-based method, compared to the other two types of tactile image sensors, lies in its superior sensitivity and resolution. In this method, each pixel points in the captured image information acts as a tracked marker with a micron-level pitch [9]. This high-resolution tracking enables tactile capabilities that surpass human touch, making the reflective membrane-based method particularly effective for precise contact measurements [10].

---

* The authors contributed equality to this paper.

⁺ Corresponding author: Chenguang Yang

An example of this technology is the elastomer layer used in Gelsight sensors. When the sensor comes into contact with the scanned object, the elastomer surface deforms. This deformation then obstructs the light, creating a shadow that mirrors the alteration. At present, the tactile image sensor based on a reflective membrane ranks as one of the most popular in the field, widely utilized in numerous versions of the Gelsight series [11-14]. Another notable implementation of this technology is seen in DIGIT, developed by Lambeta et al. [15]. DIGIT differentiates itself by substituting the aluminium powder layer with white silicone paint, a change that significantly reduces manufacturing costs. By utilizing a deep neural network (DNN), the DIGIT sensor empowers the robot's fingers to precisely move a marble, either manipulating it between positions. This innovation showcases the evolving applications and increasing accessibility of reflective membrane-based tactile sensors in advanced robotics and tactile sensing technology.

Therefore, we aim to develop an optical tactile sensor roller dedicated to real-time detection and visualization of surface defects in hand layup of composites materials. This roller, enveloped in a soft elastomer outer layer, boasts high spatial resolution, enabling it to detect surface shapes in the 3D geometry of the composites. This capability enables the detection of potential defects, including wrinkles, bridged corners, or foreign objects and debris (FOD) generated during prepreg and dry fabric hand layup. Concurrently, force and speed sensors are employed to detect abnormal slippage or clogging during the layup process, mimicking the nuanced information obtained through human tactile sensing [16]. Moreover, transitioning from a serial to a parallel inspection process drastically reduces post-layup inspection time of the total process time.

The rest of this paper is organised as follows: Section II focuses on related works provides a brief overview of various tactile sensors and their applications in detecting defects in composites. Following this, section III on tactile roller design delves into the roller's structure and fabrication methods in detail. Section IV outlines the objectives and procedures of the conducted tests. Finally, in the Section V, the findings from the tactile sensor roller tests are presented and analysed. Section VI makes a final conclusion.

II. RELATED WORKS

In hand layup, manual inspections rely heavily on visual examination and tactile assessment by humans. In contrast, modern automated inspection methods have evolved to include technologies such as thermal imaging, laser profiling, contour-based inspections, and machine learning [17]. Defects like gaps, wrinkles, and overlaps are common in manufacturing, particularly during the hand layup stage, often due to a lack of skill in manufacturing or improper handling. During hand layup, the irregularities in shape can be felt by hand, and visible defects can be spotted by the eye. However, this approach is not only time and labour-intensive but also faces challenges in accuracy, especially when inspecting composites which have reflective surfaces. Automated inspection methods provide greater precision, efficiency, and cost benefits compared to manual inspection, but they are predominantly visual and produce only 2D images. This can lead to difficulties in detecting defects when the fibre orientation aligns with the defect, as depth information is lacking. However, this challenge can be addressed through tactile perception, which provides depth information, making it suitable for examining surfaces with complex textures. For instance, the tactile sensor developed in [5] is capable of creating 2.5D tactile images, enabling robots to detect object edges and irregular shapes. By harnessing the learning capabilities of robots, they can discern surface textures as effectively as human hands.

Over recent decades, tactile sensing has emerged as a crucial technique for detecting defects that are not easily visible, especially those related to contact and the external shapes of objects [18]. A notable example is the TacTip, developed at the Bristol Robotics Laboratory (BRL), which excels in assessing 3D surface shapes [8]. Another significant development is the GelSight sensor [13], which utilizes a transparent elastomer, LED lights, and a camera. This design captures surface textures by recording the deformation of the elastomer upon contact. Similarly, the TouchRoller sensor [19] follows the same design principles but incorporates the tactile sensor into a cylindrical form. This allows the sensor to operate in a rolling motion, enhancing its sensing capabilities.

Elkington et al. have leveraged TacTip in a novel method to detect ply defects in real time during the layup process [20]. This sensor emulates the action of a human finger pressing against a surface and employs the nearest neighbour method [21] to identify differences in pin positions between test and training sets, thus pinpointing ply defects. TacTip has proven its efficacy in detecting defects on various surfaces, whether flat or complex and can even identify fractured tow defects as narrow as 3.18mm in AFP processes. Furthermore, TacTip has been applied in the automotive industry to detect alignment gaps as slight as 0.35mm in width [22]. Enhancing TacTip's decision-making capabilities, Lepora and Ward-Cherrier have integrated Bayesian theorems with sequential analysis for active perception [23]. However, it is evident that TacTip's capabilities are primarily limited to detecting submillimetre quality defects, and it struggles to accurately represent the 3D shape of these defects. Moreover, during the manufacture of composite materials, it is common to encounter large composite structures that need inspection. This reality elevates the importance of inspection efficiency. Large-scale composite structures pose a unique challenge due to their size, requiring inspection methods that are not only accurate but also efficient. To address these issues, the paper suggests modifying the shape of the sensor's fingertip into a roller form, aiming to significantly improve the efficiency of defect detection.

The reflective membrane-based tactile sensors mentioned earlier are generally designed to mimic the shape of a human finger, resulting in their primary mode of contact being through pressing [19]. While this design is somewhat effective for measuring small surfaces or inspecting limited batches of products, its efficiency significantly diminishes in real industrial applications. To address this limitation, Cao et al. introduced the TouchRoller, a cylindrical tactile sensor [19]. Unlike traditional sensors, the TouchRoller operates by rolling around its central axis, maintaining continuous contact with the surface and thereby constantly gathering tactile data. As its outer elastomer layer encounters surface irregularities like bumps, it deforms, capturing the geometry of the contact area. This allows for the reconstruction of the test surface using a sequence of images collected during the roll. In terms of efficiency, TouchRoller marks a substantial improvement, taking only 10 seconds to cover an area that would take GelSight 196 seconds [24]. A similar design to TouchRoller has been proposed by Shimonomura et al. for detecting foreign objects in food based on hardness variations [25]. When pressed against food, the elastomer layer deforms more where it encounters harder foreign bodies, leading to distorted angles in the reflected light. This distortion makes one side of the foreign object appear brighter and the other darker [26]. In their experiments, carried out on an automated production line operating at a consistent rate of approximately 30mm/s, the researchers successfully detected shells in shrimp meat, as well as fish spines and bones in minced meat. The scan of a group of foods was completed in just 10 seconds, demonstrating the potential of such tactile sensors in enhancing the efficiency and effectiveness of quality control in food processing and other industrial applications.

Indeed, the capability to measure force and speed during the inspection process is a vital aspect that both designs currently lack. Applied force is crucial in contact inspection methods, especially when inspecting composite materials. Excessive force applied by the inspection roller can compromise or even damage the quality of the composites, making the control of this force imperative. Ideally, the force exerted by the inspection roller should be comparable to that of the manufacturing roller to maintain consistency and prevent damage. Furthermore, the use of a point light source inside the roller presents another limitation. This type of light source is not conducive to generating 3D image reconstructions of detected defects. The ability to create 3D reconstructions is significant because it can provide operators with a more comprehensive view of defects, allowing for a more detailed analysis and precise judgment. This visualisation can be instrumental in identifying the nature, depth, and exact dimensions of the defects, leading to better decision-making in addressing these issues. Building upon existing designs like the TacTip, TouchRoller, and GelSight sensors, we have developed an innovative roller-shaped tactile sensor. Equipped with a reflective membrane and integrated force and speed sensors, this design offers enhanced versatility in detecting force and speed changes. This functionality makes it particularly suitable for the composites sheet layup process during inspection.

III. TACTILE ROLLER DESIGN

A. *Tactile Sensor Working Principle*

The fundamental concept behind the tactile sensor roller involves capturing the deformation patterns of the elastomer with a camera, using these images along with physical variations like force and speed during contact with the surface of the composites material as tactile data for sensory perception. Our approach employs a cylindrical tactile sensor that rolls, allowing for constant tactile input gathering without the need for vertical movement, enhancing inspection efficiency. This method of transforming physical touch into optical signals draws inspiration from the Gelsight tactile sensor, which is based on a reflective membrane.

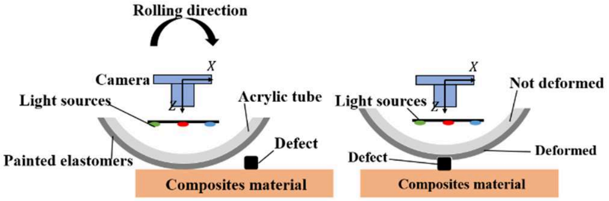


Fig. 1 Principle of the tactile roller detecting defects on the composites ply.

The operational mechanism of the tactile roller is shown in Fig.1. The clear elastomer, coated on its surface, obstructs external light, creating an optimal reflective environment for the internal light source. As the sensor encounters a defect on the composites surface, the elastomer alters shape, leading to a change in the reflection pattern at the site of the defect. The camera captures images of these defects, which are subsequently processed using a classic photometric stereo algorithm to reconstruct a 3D visualization of the inspection findings. The necessity for precise dimensional accuracy in the reconstructed defects is not a priority, as achieving such accuracy would necessitate extreme lighting conditions. These conditions are challenging to attain in a real-world industrial setting, and if feasible, would compromise efficiency. Consequently, our primary purpose is the clear differentiation between correct ply and defects in the reconstructed images, rather than detailed dimensional accuracy.

The design of the tactile sensor consists of a transparent acrylic tube, 5mm thick, encased in a 2.5mm thick gel elastomer which is presented below as Fig.2. The surface of the elastomer is evenly covered in a matte grey paint, forming a reflective layer. This gel-like elastomer, crafted from Smooth-On Solaris silicone rubber, boasts a hardness of 10A on the Shore scale. This design allows the entire exterior of the cylinder to function in tactile sensing. The camera is situated within the stationary groove of the connecting tab., capturing images of the contact area from within the cylinder. RGB LED beads are strategically attached beneath the camera to provide internal illumination without hindering the camera's view. The acrylic tube measures 60mm in inner diameter and 70mm in outer diameter, with a height of 60mm.

B. *Internal Measuring and Lighting System*

1) Connector

The connecting tab serves as the central element of the tactile sensor roller, bringing together and integrating all its components. For example, as illustrated in Fig.3, the left and right rods are connected with a pair of bushings, which in turn link the left and right wheels. The camera (a) is mounted on a sunken platform in the centre of the connecting tab, arranged to offer a downward view directly below. On the right side of the connecting tab, the force sensor (b) is situated within a through-hole. This sensor is linked on its top and bottom by respective connectors.

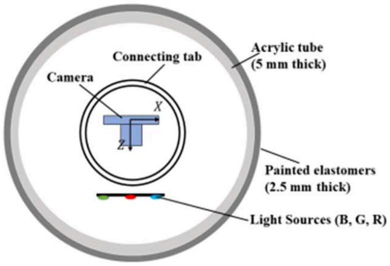


Fig. 2 Left-side perspective of the tactile roller and the configuration of light sources.

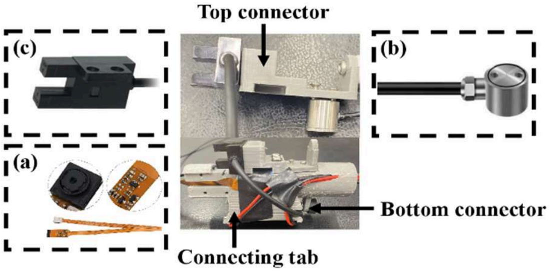


Fig. 3 Outline of the connector structures and camera.

The top connector is designed to attach the u-slot photoelectric sensor on its left side. Directly beneath, the connector is fastened to the connection tab, aiding in securing the camera in position with a groove located just below. Additionally, the force sensor, an integral part of this assembly, is positioned underneath the connector. Conversely, the bottom connector plays a pivotal role by linking the force sensor to the M10 wheel at the base. This M10 wheel, designed to be tangential, fits snugly against the inner wall of the right wheel's innermost tab, enabling precise measurement of the force exerted during rolling. The assembly also includes an embedded 5-megapixel Raspberry Pi camera module. This camera, with a field angle of 69.1°, can maintain HD resolution at a frame rate of 30 FPS and has an effective object distance of over 30mm.

2) Force Sensor

The piezoelectric force sensor, as depicted in Fig.3(b), is installed in the through hole of the connecting tab adjacent to the right wheel. It is secured between the top and bottom connectors. This sensor measures the force exerted perpendicularly to the testing surface, directed upwards towards the roller. Its functionality relies on the piezoelectric effect, a phenomenon where certain materials produce an electrical charge in response to mechanical stress or strain. This process allows the transformation of the exerted force into an electrical signal. When the tactile sensor experiences force on the object surfaces, a corresponding reaction force is exerted on the force sensor, as indicated by the red arrow in the Fig.4. Subsequently, employing the DY094 transmitter, this electrical signal is converted into analogue signals. This conversion facilitates the interpretation of the applied force.

3) Speed Sensor

The application of a U-slot photoelectric sensor, as depicted in Fig.3 (c), tracks positional variations in the gaps on the left wheel, providing a reference for assessing the rotational speed. This sensor comprises a pair of emitters and a receiver set in opposition, where the emitters produce an infrared beam captured by the receiver. The sensor's functionality is based on a Negative-Positive-Negative (NPN) transistor configuration, which includes two positive semiconductors flanked by two negative semiconductors. The process starts with the application of a minor current to the base, which initiates the current flow from the collector to the emitter. In the absence of an object, the

NPN transistor's base within the photoelectric sensor remains unbiased, preventing current flow between the collector and emitter. This state results in a high voltage output. Conversely, when an occlusion is detected, the base becomes biased, allowing a small current to enter. This action enables a more substantial current to flow from the collector to the emitter, leading to a ground output. The response time of this system, from beam interruption to NPN transistor activation, is remarkably quick, typically only a few milliseconds. This rapid response rate makes the photoelectric sensor with an NPN transistor highly effective in real-time applications.

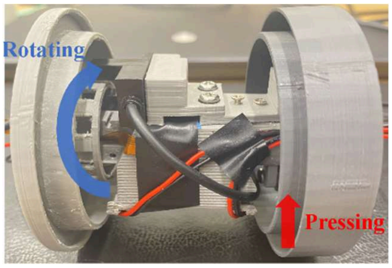


Fig. 4 The piezoelectric force and u-slot photoelectric sensor and schematic of measuring force and speed.

The innermost tab of the left wheel, featuring evenly spaced gaps, moves through the u-slot in conjunction with the roller. This motion alternately blocks and allows the passage of the beam, generating outputs of varying high and low levels. These outputs are crucial for calculating the linear speed of the roller, as indicated by the blue arrow in Fig.4. To determine the rotary speed of the left wheel, we employed the Arduino UNO R3 microcontroller which processes the signals received from the u-slot photoelectric sensor, enabling accurate speed measurements. The configuration of the light source utilized in photometric stereo is shown in Fig.5. This design selects RGB LED beads, aligning with the Gelsight tactile sensor's design [13].

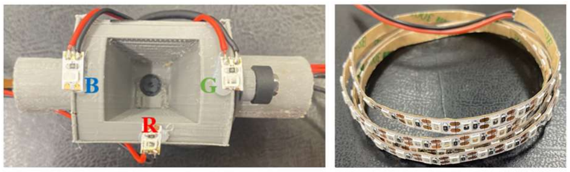


Fig.5 The layout of the LED light source

The assembly process for the camera, force, and speed sensors involves several steps. First, position the camera within the groove located at the centre of the connecting tab and secure it using insulating tape. Next, press its cable into the notch on the connecting tab's left shaft. Then, attach the photoelectric sensor to the left side of the top connector. Following this, secure the forced side of the force sensor to the underside of the top connector. Place the force sensor in the through-hole on the right side of the connecting tab, located just beneath the top connector, and then connect the top connector to the connecting tab. Finally, affix the red, green, and blue LED beads to the lower edge of the connecting tab, as illustrated in Fig.5.

C. *Outer Reflective Elastomer*

The tactile sensor roller's elastomer is composed of two distinct parts: a transparent elastomer and a reflective membrane. The transparent elastomer, essential for its clarity and flexibility, is adhered to the acrylic tube to reduce residual forces during contact. In contrast, the reflective membrane plays a crucial role in the sensor's signal quality. It needs to be uniformly thin, durable, and effective at blocking external light. Any deviation from uniformity or thinness can introduce noise into the tactile image and diminish the resolution. Smooth-On Solaris silicone, known for its high transparency, is the chosen material for the elastomer.

The bidirectional reflection distribution function (BRDF) of the gel elastomer is significantly influenced by the pigment applied to its surface. Metallic paints, known for their ability to amplify light reflections from minor changes in the object's surface normal, offer high gain. This characteristic makes them particularly effective in making small surface undulations highly visible. On the other hand, matte coatings are preferable for the accurate measurement of general shapes, owing to the diffuse reflection they generate. Furthermore, the choice of grey as the pigment colour is strategic. Its spectral-free nature avoids any colour reaction, providing ideal contrast. This neutrality in grey enhances the visibility of contours, making it a superior choice for applications where clarity and detail are paramount.

D. *Wheels and Handles*

The linkage between the left and right wheels and handles, along with their respective outlines, is displayed in Fig.6. It is important to note that these components have distinct dimensions, reflecting their different functions. The left wheel is designed to estimate rolling speed, featuring ten evenly spaced gaps on its innermost tab. Conversely, the right wheel is engineered for measuring force perpendicular to the composite material's surface, with a design that allows the innermost tab's inner wall to seamlessly fit into the M10 wheel, facilitating precise force measurement. The left and right handles are attached to the cylindrical shafts of the connecting tab on their respective sides. Additionally, power wires for the light sources run through two extra holes in each handle, eventually connecting to the coin cell battery holders within the handles' grooves.

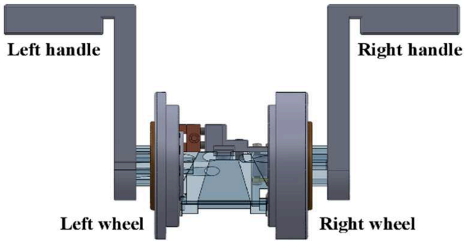


Fig. 6 Outline of the wheels and handles structures.

IV. EXPERIMENTS

The objective of these experiments is to assess the effectiveness of the tactile sensor roller in identifying surface defects on composites, such as wrinkles, foreign objects beneath the ply, and overlaps. A key focus is to clearly distinguish these defects by capturing and analysing both physical parameters like force and speed, and tactile image data. Additionally, the efficiency with which the tactile sensor roller can inspect the surface quality of composites materials, especially when the defect locations are unknown, is also under scrutiny. The configuration of the experimental setup is illustrated in Fig.7. Initially, the wire from the force sensor connects to the DY094 transmitter, which is powered by an external 24V DC source, and then it links to a USB port on the laptop. The wire from the photoelectric sensor is connected to the Arduino UNO R3 and then to another USB port on the laptop. As for the camera, its cable is connected to the laptop's USB port through a 15-pin/csi converter. Consequently, this setup allows for the real-time monitoring of tactile images, along with force and velocity data, as the composites material undergoes examination in experimental scenario B. These observations are displayed on the laptop screen and recorded for later data analysis. The computer processes the analogue signal from the force sensor, broadcasting it at 0.2-second intervals. Meanwhile, the Arduino serial plotter captures the rolling speed during the defect detection, and the camera documents the whole procedure of examining the composites ply surface with the tactile sensor, aiding in the identification of any defects.

The initial experiment shown in Fig.8(a) focuses on gathering visual and tactile data on defects whose locations are already known, as well as understanding the limitations of defect detection. For this purpose, various artificially created manufacturing defects were introduced for the tactile sensor to detect. This test evaluates the sensor's effectiveness in a static state, solely through pressing actions. We used four woven dry fabric sheets, each 10cm long, 12cm wide, and 0.5mm thick. The setup involves a table that serves as the mould, onto which the fabric sheets are layered. The likelihood of defects occurring between the mould and the first layer of the fabric is minimal. This is because the mould is thoroughly cleaned and treated with a release agent before the layup process, ensuring a strong and defect-free bond between the mould and the initial fabric layer. Therefore, the defects are positioned between the first and second layers of woven fabric. As depicted in Fig.9 (b) (c) (d), three common defects in the layup of woven fabric are considered: wrinkles, foreign objects and debris between plies, and overlaps.

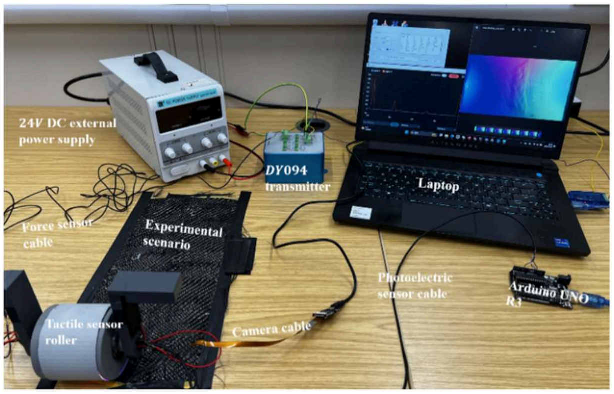


Fig.7 The overall layout of the experiment setup

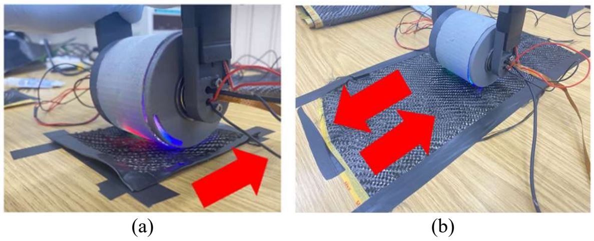
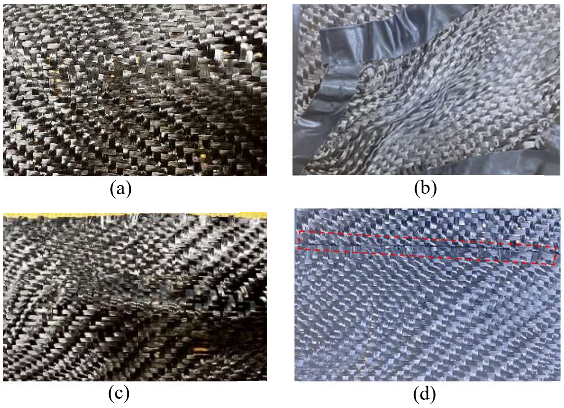

(a) (b)

Fig.8 The overall experimental scenario: (a) inspection with the known defects. (b) inspection with the unknown defects

The subsequent phase, Fig.8 (b), of the experiments is designed to mimic a full surface inspection of the composite fabric, to identify defects in scenarios where the locations of these defects are not known beforehand. This step is crucial in testing the sensor's ability to detect and pinpoint imperfections effectively across the entire composites surface under uncertain conditions. We made a single piece of woven fabric measuring 35cm in length, 18cm in width, and 0.5mm in thickness. This piece contains two types of defects intentionally placed beneath it which include foreign objects between the plies and a wrinkle. Identifying these defects through overhead photographic imagery is challenging, as it is hard to discern their presence or exact location without physically touching them. In this scenario, we manually operate the tactile roller to methodically examine the fabric. Following the path indicated by the red arrows in Fig.8(b), the exploration begins from the lower right edge of the fabric. The process involves rolling the sensor forward to the opposite end, lifting it, shifting slightly to the left, pressing down again, and then rolling it back towards the starting point, thus ensuring a thorough examination of the fabric surface for any hidden defects.


(a) (b)

(c) (d)

Fig.9 Defects set up in the initial experimental, where (a) correct ply, (b) wrinkled ply, (c) foreign object and debris (FOD) included ply, (d) overlapped ply.

Wrinkles in the woven fabric can arise from various factors such as its uneven placement initially, the use of inappropriate layup tools, inconsistent application of force during layup, or the material's ageing. Similarly, the presence of foreign materials between layers often results from leftover adhesive or fragments of older fabric. Overlaps are typically caused by the shifting or twisting of the fabric during the lay-up process. When these defects are present, the operator assesses the surface of the fabric either visually or by touch, and in some cases, employs sophisticated tools like ultrasonic scanners or infrared thermal imagers for a more precise evaluation. To rectify these defects, the operator manually adjusts the layers – smoothing out wrinkles using a roller, extracting foreign objects with tweezers, or realigning the edges of the layers with a spatula. The ultimate goal is for the tactile sensor roller to take over these manual inspection tasks. Consequently, machines are expected to primarily manage the detection of surface defects in woven fabric, greatly minimizing human intervention.

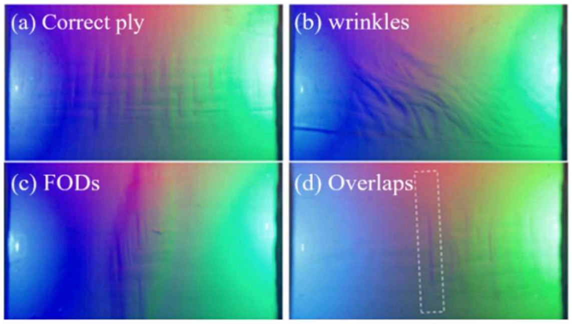


Fig.10 Tactile images of the defects in the initial experimental: (a) correct ply, (b) wrinkles, (c) FODs (d) overlap

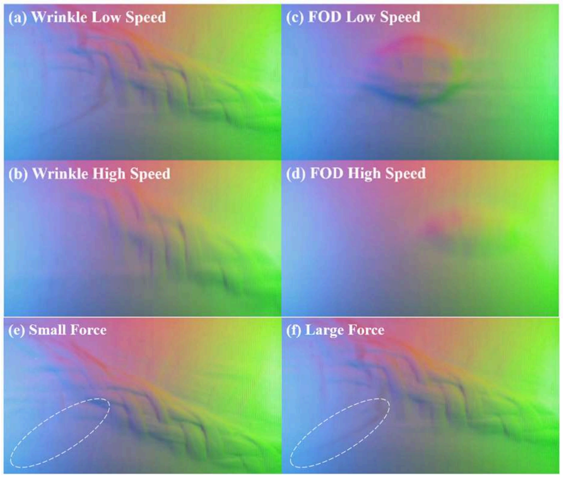


Fig.11 Tactile images of the defects extracted from the videos at high and low rolling speeds and force data.

Tactile images of the proper ply, wrinkles, foreign objects between plies, and overlap are presented in Fig.10. In these images, the wrinkles and the foreign object between layers are distinguishable from the correct ply. However, the overlap, marked by a white dashed box, is harder to detect as it appears merely as a straight line of shading in the image. It is important to note that the lighting in these four images is less than ideal. More specifically, there are strong reflections on both sides with the blue and green light. These reflections create a halo effect, strongest at the centre and fading as they spread radially outward. The green light is notably brighter than the blue, leading to inaccuracies in 3D image reconstruction, particularly in generating normal maps. In contrast, the red-light source is optimal due to its lack of reflections and appropriate brightness level. This discrepancy is likely due to the camera's field of view, both vertically and horizontally, which encompasses the square space beneath the connecting tab. To enhance future image quality, reducing the horizontal field of view might be worth considering. As a result, cropping the tactile images of the defects to an appropriate size is necessary to minimize the loss of light and dark details, as well as to prevent colour distortion in areas affected by these strong reflections.

In the second experiment, we evaluated the tactile sensor roller's performance by inspecting a woven fabric sample at varying speeds. This process involved the simultaneous recording of both force data and tactile images, as illustrated in Fig.11. The results indicated that peaks in force data typically coincided with encountering defects in the material. Interestingly, we found that greater force application led to clearer texture images. However, this poses a conundrum: while increased force improves accuracy in defect detection, it also raises the risk of damaging the material if the force is excessive. Furthermore, our analysis of the tactile images obtained at low and high speeds revealed a clear pattern: the quality of the images was significantly superior at lower speeds. On the other hand, images captured at high speeds exhibited a considerable loss in surface texture detail and inconsistent brightness levels. These observations underscore the critical importance of speed control in effectively utilizing the tactile sensor roller for defect detection in composite materials.

V. CONCLUSION

In summary, this paper introduces a novel optical tactile sensor roller designed for defect defection in large-area composites during the hand layup process. This innovation addresses the limitations of traditional fingertip-type tactile sensors, which are hindered by their small detection areas. This tactile sensor roller not only visualizes but also captures the 3D shape of composites surfaces. Moreover, it utilizes force and velocity measurements as supplementary reference points, enhancing its effectiveness in defect detection. In the experiment, tactile images of defects were markedly distinct from those of the undamaged surface, demonstrating the novel tactile sensor's proficiency in differentiating between healthy composites and defects. However, the images' edges exhibit brightness inconsistencies and a decrease in sharpness. The hypothesis for these errors includes the light source configuration, particularly the uneven brightness of the blue and green LEDs positioned on both side edges of the image. Nevertheless, it stands out in terms of detection efficiency and offers a cost-effective, economical solution for situ inspection.

One of the limitations of this paper comes from the grey matte finish on the outside of the elastomers, as the ideal Lambertian surface does not exist in reality. Secondly, the LED beads are not ideal point light sources and reflections and refractions caused by the transparent acrylic tubes are unavoidable. Therefore, we propose to introduce new photometric stereo algorithms to model non-Lambertian surfaces, or to use machine learning to establish a mapping between the light source and the reconstructed image.

REFERENCES

[1] Elkington, M., Bloom, D., Ward, C., Chatzimichali, A., & Potter, K. (2015). Hand layup: Understanding the manual process. Advanced Manufacturing: Polymer & Composites Science, 1(3), 138–151.

[2] Squatriglia, C. (2010, November). Peek inside the Chevrolet Volt Factory. Wired. https://www.wired.com/2010/11/peek-inside-the-chevrolet-volt-factory/

[3] Taub, A., De Moor, E., Luo, A., Matlock, D. K., Speer, J. G., & Vaidya, U. (2019). Materials for automotive lightweighting. Annual Review of Materials Research, 49, 327–359.

[4] Creaform. (2023). Go!SCAN 3D. https://www.creaform3d.com/en/handheld-portable-3d-scanner-goscan-3d/technical-specifications

[5] Shimonomura, K. (2019). Tactile image sensors employing camera: A review. Sensors, 19(18), 3933.

[6] Hiraishi, H., Suzuki, N., Kaneko, M., & Tanie, K. (1988). An object profile detection by a high-resolution tactile sensor using an optical conductive plate. In Proceedings. 14th Annual Conference of Industrial Electronics Society (Vol. 4, pp. 982–987).

[7] Sferrazza, C., & D'Andrea, R. (2019). Design, motivation and evaluation of a full-resolution optical tactile sensor. Sensors, 19(4), 928.

[8] Nozu, K., & Shimonomura, K. (2018). Robotic bolt insertion and tightening based on in-hand object localization and force sensing. In 2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM) (pp. 310–315).

[9] Johnson, M. K., & Adelson, E. H. (2009). Retrographic sensing for the measurement of surface texture and shape. In 2009 IEEE Conference on Computer Vision and Pattern Recognition (pp. 1070–1077).

[10] Johnson, M. K., Cole, F., Raj, A., & Adelson, E. H. (2011). Microgeometry capture using an elastomeric sensor. ACM Transactions on Graphics, 30(4), 46:1–46:8.

[11] Yuan, W., Li, R., Srinivasan, M. A., & Adelson, E. H. (2015). Measurement of shear and slip with a GelSight tactile sensor. 2015 IEEE International Conference on Robotics and Automation (ICRA), 304–311.

[12] Li, R., & Adelson, E. H. (2013). Sensing and recognizing surface textures using a GelSight sensor.

[13] Li, R., Platt, R., Yuan, W., et al. (2014). Localization and manipulation of small parts using GelSight tactile sensing. In 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems (pp. 3988–3993).

[14] Lepora, N. F., Church, A., de Kerckhove, C., Hadsell, R., & Lloyd, J. (2019). From pixels to percepts: Highly robust edge perception and contour following using deep learning and an optical biomimetic tactile sensor. IEEE Robotics and Automation Letters, 4(2), 2101–2107.

[15] Lambeta, M., Chou, P.-W., Tian, S., et al. (2020). DIGIT: A novel design for a low-cost compact high-resolution tactile sensor with application to in-hand manipulation. IEEE Robotics and Automation Letters, 5(3), 3838–3845.

[16] Yuan, W., Dong, S., & Adelson, E. (2017). GelSight: High-resolution robot tactile sensors for estimating geometry and force. Sensors, 17(12), 2762.

[17] Brasington, A., Sacco, C., Halbritter, J., Wehbe, R., & Harik, R. (2021). Automated fiber placement: A review of history, current technologies, and future paths forward. Composites Part C: Open Access, 6, 100182.

[18] Jentoft, L. P., Tenzer, Y., Vogt, D., Liu, J., Wood, R. J., & Howe, R. D. (2013). Flexible, stretchable tactile arrays from MEMS barometers. In 2013 (ICAR) (pp. 1–6).

[19] Cao, G., Jiang, J., Lu, C., Gomes, D. F., & Luo, S. (2021). TouchRoller: A rolling optical tactile sensor for rapid assessment of large surfaces.

[20] Elkington, M., Almas, E., Ward-Cherrier, B., et al. (2021). Real time defect detection during composite layup via tactile shape sensing. Science and Engineering of Composite Materials, 28(1), 1–10.

[21] Ward-Cherrier, B., Pestell, N., Cramphorn, L., et al. (2018). The TacTip Family: Soft optical tactile sensors with 3D-printed biomimetic morphologies. Soft Robotics, 5(2), 216–227.

[22] Chandola, V., Banerjee, A., & Kumar, V. (2009). Anomaly detection: A survey. ACM Computing Surveys, 41(3), 15:1–15:58.

[23] Lepora, N. F., & Ward-Cherrier, B. (2016). Tactile quality control with biomimetic active touch. IEEE Robotics and Automation Letters, 1(2), 646–652.

[24] Dong, S., Yuan, W., & Adelson, E. H. (2017). Improved GelSight tactile sensor for measuring geometry and slip. In 2017 IEEE/RSJ (IROS) (pp. 137–144).

[25] Shimonomura, K., Chang, T., & Murata, T. (2021). Detection of foreign bodies in soft foods employing tactile image sensor. Frontiers in Robotics and AI, 8.

[26] Yeom, C., Chen, K., Kiriya, D., Yu, Z., Cho, G., & Javey, A. (2015). Large-area compliant tactile sensors using printed carbon nanotube active-matrix backplanes. Advanced Materials, 27(9), 1561–1

An innovative tactile sensor roller for composites inspection

Lu, Zhenyu

2024-06-05

Lu Z, Li X, Li T, et al., (2024) An innovative tactile sensor roller for composites inspection. In: 2024 IEEE International Conference on Industrial Technology (ICIT), 25-27 March 2024, Bristol, UK

https://doi.org/10.1109/ICIT58233.2024.10540981