Internship report 2023

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Contactless verification of tow width, in real-time

(lite version)

Most 3D plastic printing methods primarily employ thermoplastic materials to shape an object by melting and fusing the material. In order to maintain precise control over the shape and the progression of the printing process without physically touching the object, I designed a non-contact measurement system based on the 3D profile of a laser beam interacting with the object. My particular focus was on assessing the width of a flattened strand comprised of continuous composite fibers. To accomplish this, I utilized a webcam to capture an image of the laser beam as it interacted with the strand. By extracting the laser's path as a line in the image and comparing it to the expected straight path, I could estimate the distance of the strand from the ground, from which I could derive its width using a thresholding technique.

Contents

1 Introduction

1.1 Context

The team at The Factory Lab of Colorado State University (CSU) is currently engaged in the development of a 3D printer designed for continuous fiber-reinforced composites. This printer operates on the Big Area Additive Manufacturing (BAAM) technology, which allows the production of parts with stiffeners. These stiffeners play a crucial role in enhancing mechanical strength, as illustrated in Figure 1.

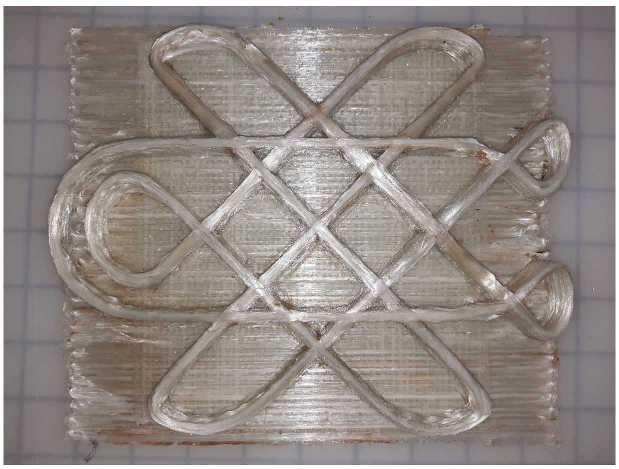

Figure 1: Illustration of a structure with printed fibers

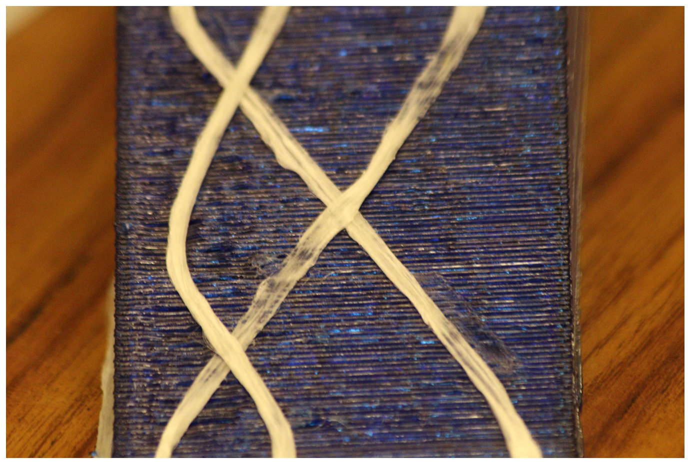

Figure 2: Variation in tow width due to uncontrolled pressure

In the process of printing parts with continuous fiber reinforcement, tows are subjected to pressure from a roller, with the applied pressure varying based on the height of the print-head. The roller compresses the tows, resulting in an increase in their width, which is closely linked to their stiffness. Notably, there is a lack of closed-loop control over the stiffness of the tows (as seen in Figure 2) as well as their width, leading to potential variations that can impact the mechanical properties of the final part.

1.2 Objectives

To address the challenges arising from the absence of control over applied pressure, it is imperative to dynamically adjust the height of the print-head throughout the printing process. As a result, our primary objective is to incorporate visual inspection of the part to effectively regulate the Z-axis, and consequently, the applied pressure.

The secondary goal, which unfortunately remains unachieved, was to ensure the tows make contact with each other to eliminate gaps between them.

2 Specification and directions

Certainly, I'll help you revise and rephrase the content in your LaTeX document. Here's the improved version:

2.1 Specifications

The laboratory aims to detect thin layers of compressed tows and obtain real-time measurements of their width to control applied pressure accurately. The specifications are detailed in Table 1:

Function	Criteria	Accuracy
Detecting the width of thin tows	Detect variations as small as *0.1mm*	Up to *0.3mm*
Minimizing latency	Fast enough to maintain pressure regulator performance	*Minimal delay*
Maintaining a low-cost project	As cost-effective as possible	*Economical*
Preventing tow deformation	Non-contact method	
Mountable on the nozzle	Dimensions and geometry must align with the CAD	The nozzle design is incomplete

Table 1: Specifications

Due to the lack of precision in these specifications, I decided to experiment with a proof of concept using equipment already available in the laboratory.

2.2 Comparison and Selection of a Concept

Traditional methods such as *stereovision* [3] or a combination of a camera and infrared sensors [9] involve expensive components. As a proof of concept, I chose to explore the use of cost-effective, simple devices. After researching various solutions (Table 2), I opted to use a basic linear laser with a standard webcam and apply the principle of structured light to detect variations in tow thickness.

Indeed, *H. Yu and his team* [11] used this method to estimate surface roughness during an additive manufacturing process and achieved roughness estimates with an accuracy of *0.01mm* (Figure 3). I assumed that this level of accuracy was sufficient

Stylus	Real-time	Contact
Interferometer [5]	Contactless, High precision	Expensive, not real-time
Laser [4]	Contactless	Not real-time
Stereo vision [3]	Real-time, Contactless	Expensive, slow
Structured light [11]	Real-time, Contactless	Limited angle, low contrast

Table 2: Existing Solutions, Advantages, and Drawbacks

for analyzing the shape with a more affordable laser and camera setup, achieving an accuracy of about *0.1mm*.

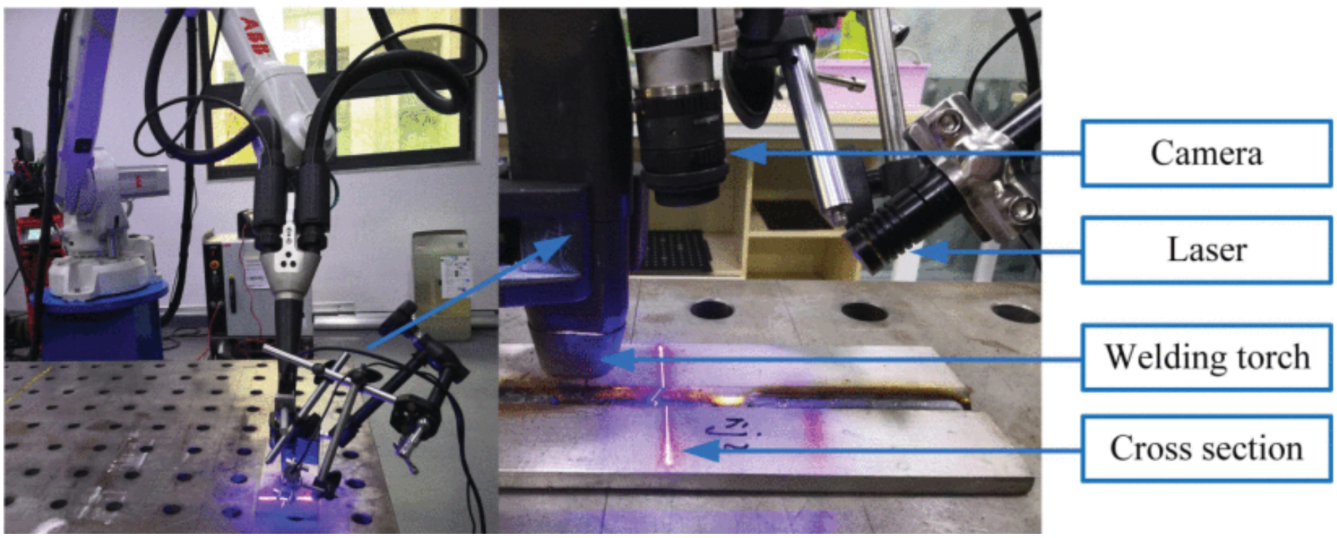

Figure 3: Experiment by *Yu and his team*

2.3 Methodology and Approaches

Because the requirements differ between roughness estimation and edge identification, the image processing methods developed by *H. Yu and his team* cannot be directly applied to our situation. It clearly indicates the presence of information (in the Shannon sense), and I identified three strategies to achieve our goal:

- Analyzing the intensity along the laser line and applying filters to enhance interesting edges.

- Zooming in to analyze variations in the width of the laser line; the width of the line will appear thinner in a depression and wider on a bump.

- Extracting the contours of the line, separating the front and rear lines of the contour, and finding the separations between each tow by thresholding the derivative.

Each strategy has been studied and developed in the following sections.

2.4 Setup

The setup evolved during the internship, but the underlying principle remained consistent (Figure 4). I experimented with various cameras until I found a customizable webcam that met my requirements:

- A DSLR for initial experiments.
- A USB microscope for micro-analysis.
- A webcam with limited settings for the final experiment.
- Finally, a webcam with all adjustable parameters.

All image processing was performed using *OpenCV* [2].

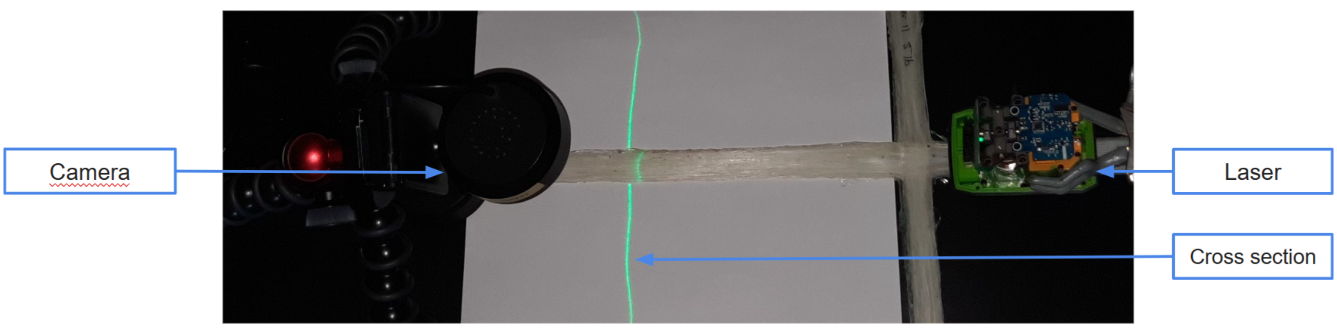

Figure 4: The setup used for most experiments

3 1^{st} strategy : enhancement of separations between tows

To detect gaps between two tows along the laser line, our initial approach was to extract a representative line from the laser profile, measure the intensity of each pixel along this line, and then apply a filtering process to highlight drops in intensity at a lower frequency. It was assumed that higher frequencies would represent the separation between fibers.

3.1 Extraction of a Representative Line

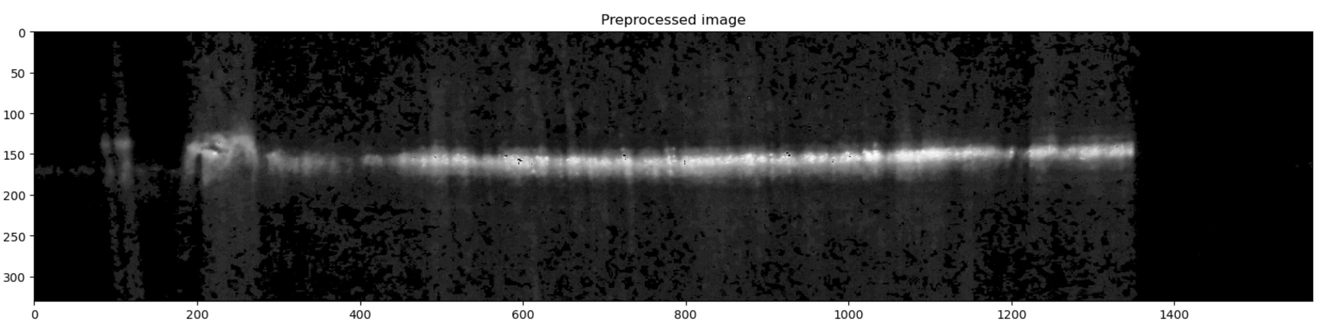

Figure 5: A typical image of a tow

A typical image of the tow is illustrated in Figure 5. The laser line is initially isolated using contour detection, and three types of lines can be extracted from it:

- A *mean-square* line, which traverses the contour from left to right.
- A *RANSAC* line[12], which fits the most linear part of the contour.
- A projection of the contour's skeleton[7], which is always contained within the contours.

Because two tows may have different heights, the *RANSAC* line may not span the entire width of the beam, and the *mean-square* line may encounter the same limitation. The optimal solution is to employ a *skeletonization* algorithm (as shown in Figure 6) and then analyze the contrasts along the generated line. However, a filtering process is required to eliminate all the branches. The main challenge is that the skeleton may not cross the contour from left to right, so if the contour extraction results in several thin contours rather than a single large one, there could be gaps in the projection. This phenomenon is more likely to occur when there is a significant difference in height between two tows.

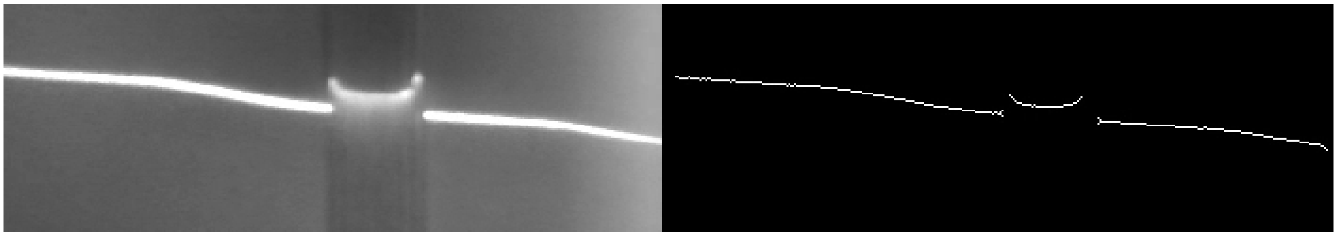

Figure 6: The skeletonization return the heart-line of a contour

Given that my primary goal was to demonstrate a concept, I chose to initially focus on the *mean-square* line and work with captures that did not exhibit these complex situations.

3.2 Signal Filtering

Performing a Fourier transform on the line allowed us to enhance frequencies associated with significant drops in intensity, which correspond to separations between two tows. Even though the tows may have varying widths, the scale relative to the size of the fibers is consistent, making a simple low-cut filter effective at accentuating the gaps (see Figure 7). Another approach considered was applying the filter directly to the captured image, as shown in Figure 8. However, even with the use of a Hanning window function, the filtered image exhibited numerous artifacts that hindered accurate processing.

3.3 Analysis of the Filtered Line and Width Detection

In order to analyze drops in intensity, we estimated the derivative of the line and applied a thresholding operation (see Figure 9). However, due to the reflection of light on dust particles and occasional anomalies in the tow, low-frequency artifacts, which accumulated due to aliasing, became prominent and distorted the analysis. This made it impossible to deterministically identify the widths of the tows.

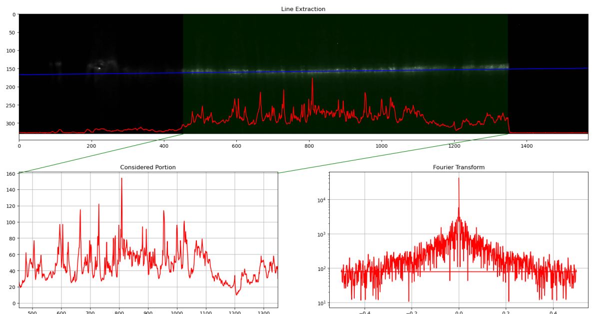

Figure 7: Fourier Transform of the line

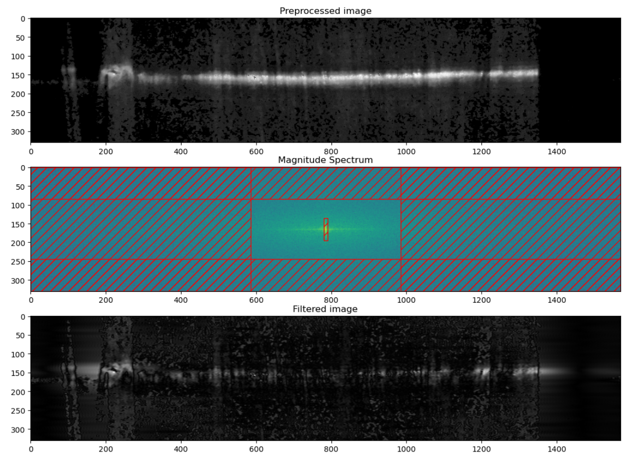

Figure 8: Fourier Transform of the image and filtering

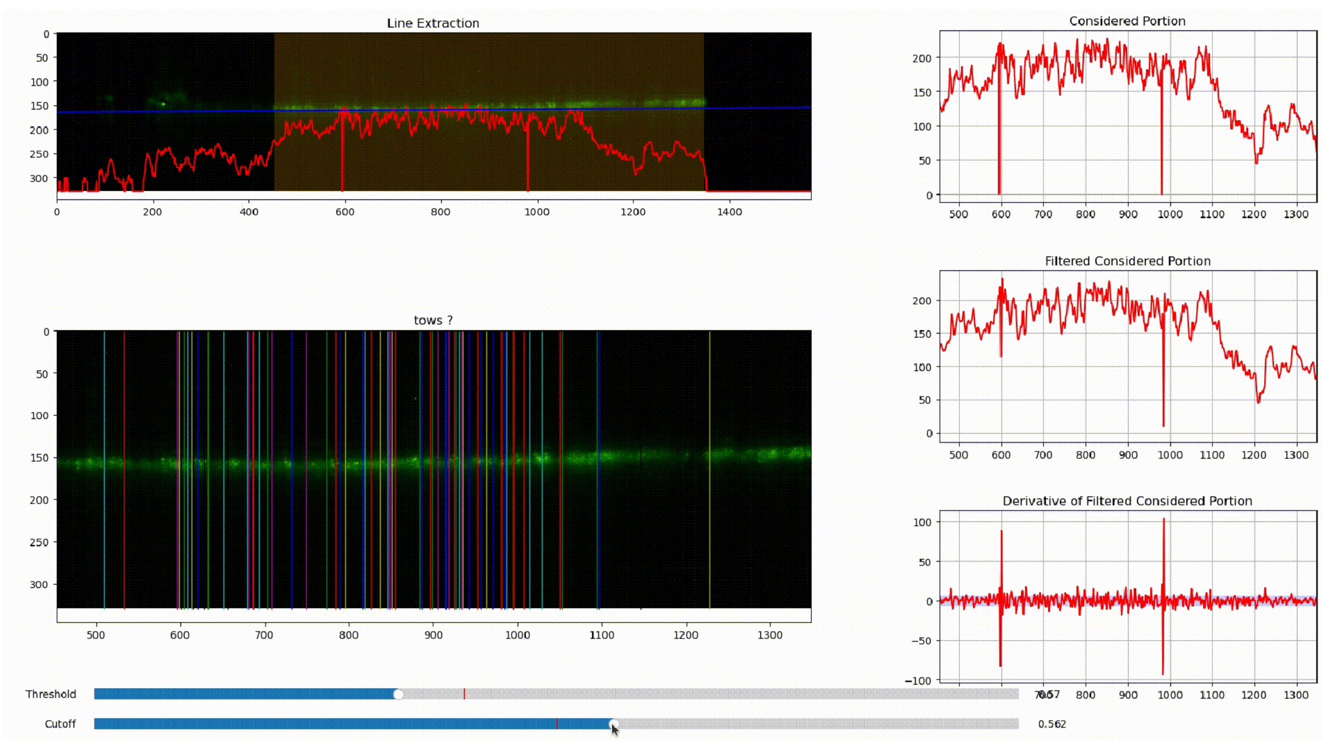

Figure 9: Filtered Signal of Contrasts

4 2^{nd} strategy : variations of width of the laser line

I attempted an alternative approach for assessing the width of the tows: observing them through a microscope, which offers greater precision in detecting their edges. The objective was to detect each border and reconstruct the shape using visual mapping techniques based on odometry or SLAM. The following process is outlined below, although it ultimately proved unfeasible to obtain meaningful information within the constraints of our timeline. As a result, the third strategy is now the preferred choice.

4.1 Description of the Process

Using a microscope, we analyzed the deviations in light caused by the fine details of the fibers (see Figure 10). By determining the relative positioning of the robotic arm and the camera, along with the arm's position, we aimed to create a highly accurate map through the application of *Structure From Motion*[6] and Kalman filtering.

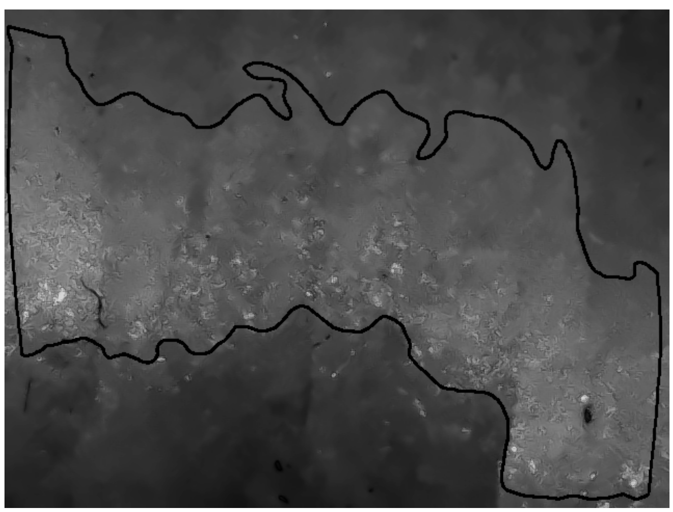

Figure 10: The laser is deviated by the bumps and holes between fibers, allowing us to isolate this shape.

4.2 Extraction and Filtering

At this scale, the aperture of the microscope's lens is smaller compared to standard webcams, resulting in better contrast between the illuminated beam and the rest of the image. Consequently, it becomes easier to extract the shape of the beam through contour detection (refer to Figure 11).

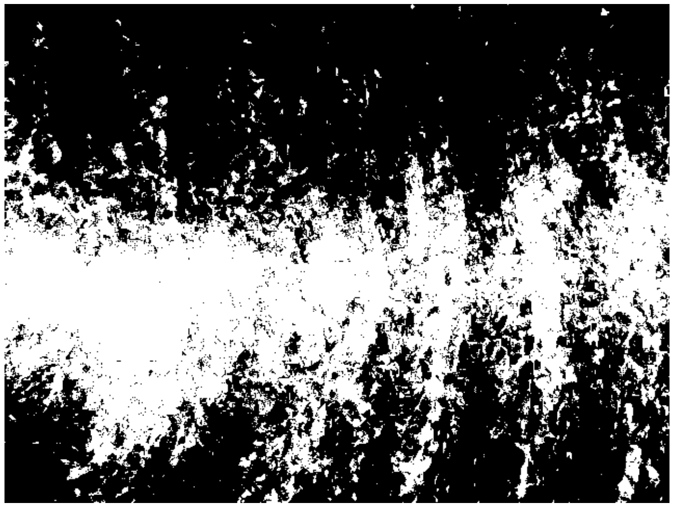

Figure 11: Before any filtering, the mask obtained from contour detection is quite rough.

However, this heightened sensitivity also makes us susceptible to dust and various unwanted reflections, resulting in artifacts such as uneven edges. To address this, I applied a *Savitzky-Golay filter*[8], which is a morphological filter that preserves the signal's integrity, in order to obtain a smoother edge for the contour (see Figure 12).

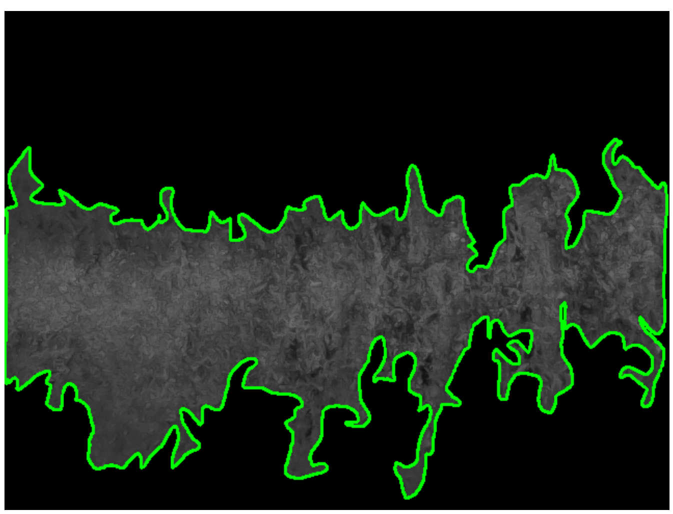

Figure 12: The *Savitzky-Golay* filter eliminates all irregularities.

4.3 Challenges and Abandonment

To reconstruct the 3D shape with this technology, I needed to address several key issues:

- Calculate a reference line for the image to estimate the deviation.
- Compensate for the distortion of the microscope.
- Obtain precise information about the camera's pose, which is attached to the nozzle mounted on the robotic arm.

Each of these points presented its own set of challenges:

- Calculating a reference line as a mean line proved impractical due to the sample's high level of magnification.
- Calibrating a microscope is more complex than other cameras due to the lens's limited focus range and the size of the sight.
- Determining the camera's position on the nozzle and developing an API for retrieving the nozzle's current location were required tasks.

These challenges led me to explore other, more easily testable solutions, such as the third strategy.

5 3^{rd} strategy : contours extraction

The final (and most effective) solution was to analyze the deviated laser beam as two distinct curves, one for the front and one for the rear, in order to estimate the derivative and establish a threshold for detecting the edges of each strand.

5.1 Line Detection

A typical image is shown in Figure 13. I conducted my experiments on pre-printed samples, where thermal contraction accentuated the edges of the strand.

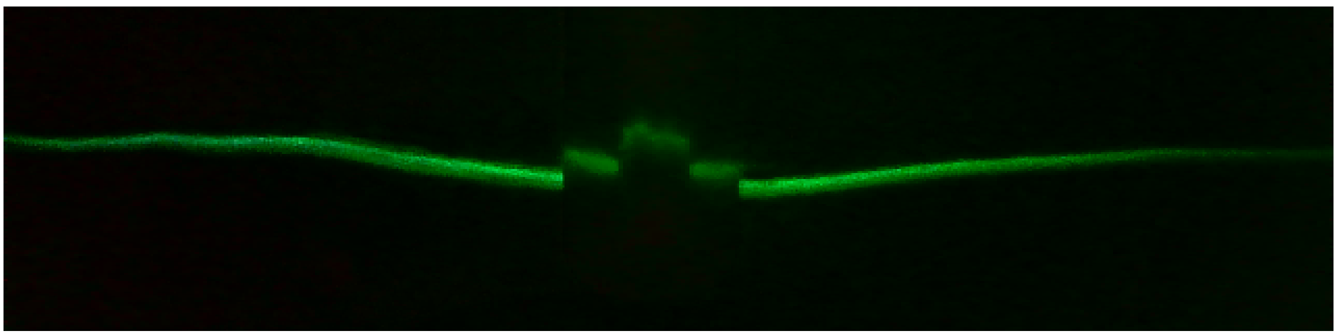

Figure 13: A typical acquisition after basic image processing

The greater the tilt of the laser beam, the more pronounced the deviation when it touches the strand. However, I was using a standard laser level, so increasing the tilt led to more artifacts and a reduction in contrast. To improve the contrast and reduce artifacts, I intercepted the beam with a razor blade, although this introduced diffraction patterns. Therefore, the tilt angle represents a compromise between diffraction and sensitivity.

To extract the strand, I employed a hue threshold and conducted contour extraction. The main challenge was merging the contours to separate the front and rear lines of the laser. To achieve this, for each contour:

- I identified the leftmost and rightmost laser points,
- I traversed the list of points in both directions to sort the upper and lower points.

Finally, I concatenated all the half-contours to estimate the front and rear lines of the laser, as shown in Figure 14.

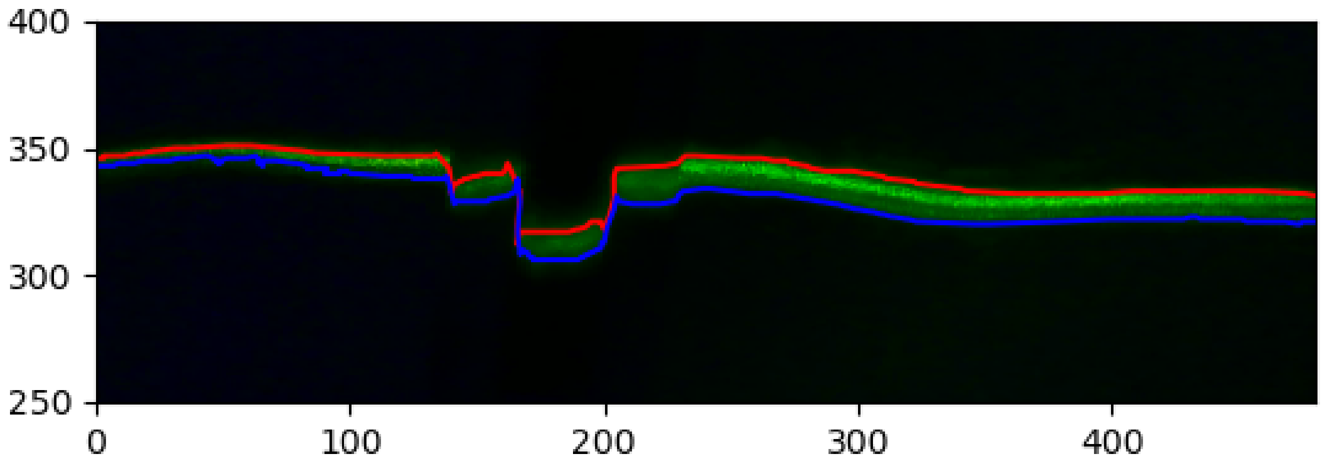

Figure 14: Both the front and rear lines fit the beam; each can be used for increased accuracy

5.2 Extraction and Interpretation

Standard morphological filtering was used to clarify the lines and remove noise. The size of the kernel depended on the noise order and had to be small enough to remove noise while preserving significant local derivatives. Following filtering, thresholding the derivative was considered efficient for extracting the width (in pixels), as seen in Figure 15.

The width can be estimated by inversing the perspective projection, considering the focal length and the distance between the camera and the surface, using epipolar geometry[10]. Nevertheless, it's important to note that the width is measured where the light touches the strand, so as the obstacle's height increases, the line deviates more, resulting in a width measurement farther from the main line, as illustrated in Figure 16.

To estimate this shift, an accurate calibration of the process could be effective, although I did not implement it, which involves:

- Calculating the reference elevation at 0,

- Extracting the most valuable line using a RANSAC method to estimate the initial height of the printing surface (the offset),

- Measuring the shift using the method described above,

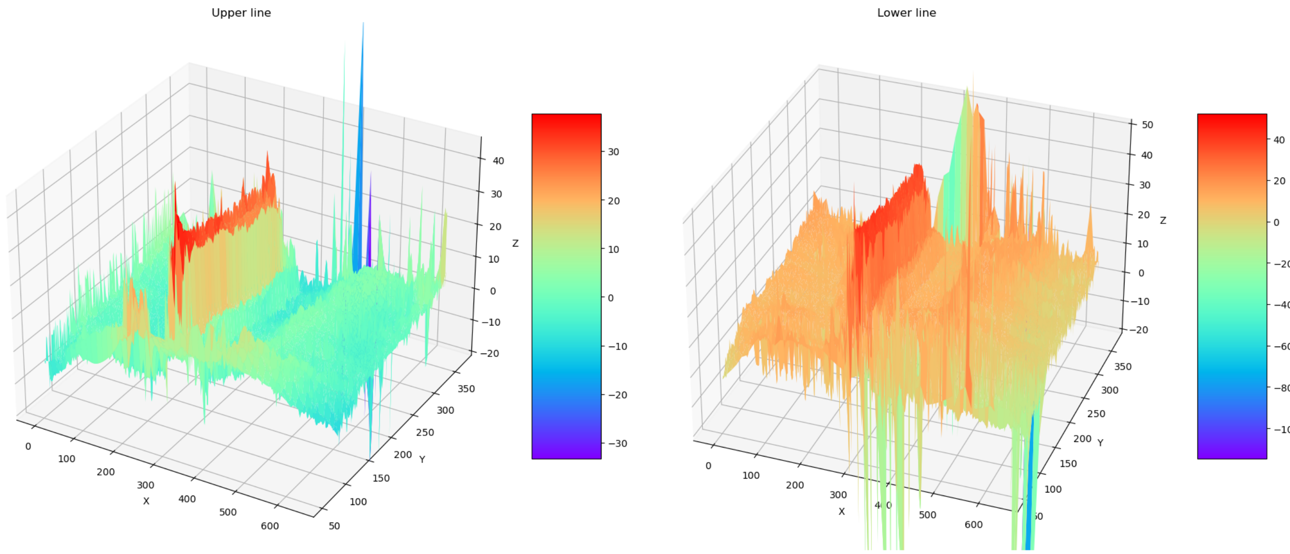

Figure 15: Real-time 3D scanning based on the front and rear lines

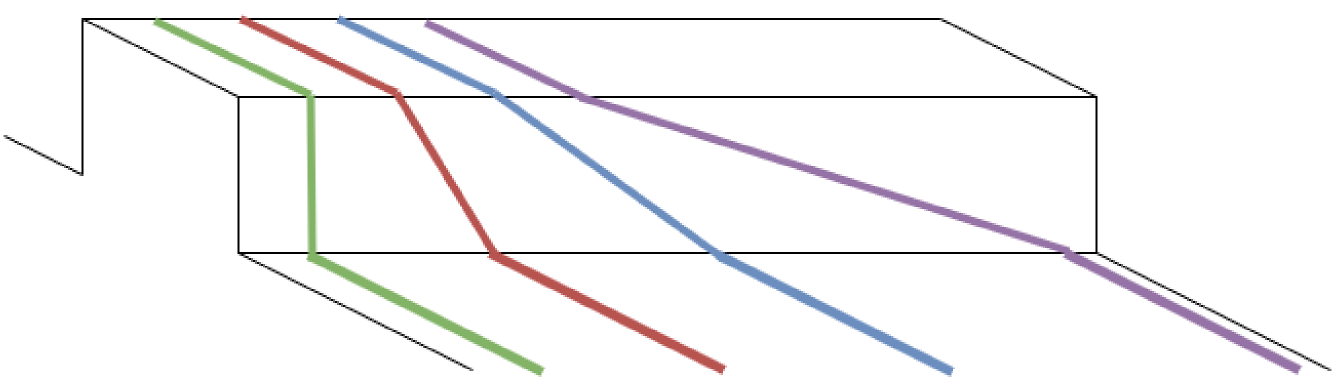

Figure 16: for different angles of the incident beamn, with a point-of-view from above, the shifting changes

- Determining where the width is measured based on the relationship between the shift and the height variation.

This raises a new challenge: while scanning is relatively easy to implement, the information regarding the delay between width measurement and control command depends on the shape and is not constant. This could lead to suboptimal control of the nozzle or instabilities.

5.3 What's Next?

So far, I have only utilized the front edge of the laser. However, I believe that merging both the front and rear edges could enhance the accuracy of the measurement system to reach 0.1 mm (as shown in Table 1). The main issue is that these two edges provide the same information, but with an undeterministic temporal delay and a different set of points. Most of the solutions I envisioned to merge these two datasets would be post-processing, at the end of the scanning process, which doesn't align with the need for real-time width estimation for the control loop. Additionally, I have not yet implemented the control loop.

Finally, the entire code was initially developed in Python using the OpenCV framework. The lag between acquisition and data processing was approximately 3 seconds. To deliver better performance while maintaining readability for lab members, I spent time developing the entire program in *Julia*[1] as shown in Figure 17.

```python
Up, Low = [], []
sleep(1)
print("Press Ctrl+C to stop")
while True:

    try :
        frame = cam.read(canal)

        struc.set_img(frame)
        struc.calculate_contours()
        struc.extract_from_contours()


        deriv = np.abs(np.diff(struc.upper[:struc.i_up,1]))
        if max(deriv) < 100:
```

Python code

```julia
params_interface(cam)
while true #take!(channel_running)==true
    img = picture(cam, 2)
    cnt = calculate_contours(img)
    l1, l2 = extract_from_contours(cnt)
    if !islocked(mutex)
        @lock mutex begin
            line1[] = l1
            line2[] = l2
        end
    end
```

Julia code

Figure 17: Both Python and Julia languages are readable, with Julia being compiled and Python being more developed.

6 Conclusion

In conclusion, the primary objective of implementing a regulation of applied force based on laser width estimation for a bundle of fibers was not achieved. However, this project provided valuable insights and learnings through the exploration, comparison, and testing of various image processing strategies. Working on real-time image processing in a materials laboratory allowed me to bridge different fields of study, uncover new challenges in robotics and computer science, and confront the complexities involved in the development of an entire system, from optimizing calculations to real-world system implementation with practical constraints. All of these aspects are central to my initial and primary career path in *Mechatronics*.

Furthermore, working independently and navigating through challenges and deadlocks has honed my decision-making skills. I believe this experience has prepared me for potential future endeavors in similar environments, and I would approach such situations with greater confidence and expertise.

References

[1] Julia language. `https://julialang.org/`.

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[12] Marco Zuliani. Ransac for dummies. *Vision Research Lab, University of California, Santa Barbara*, 2009.

RAPPORT D'EVALUATION
ASSESSMENT REPORT

Merci de retourner ce rapport par courrier ou par voie électronique en fin du stage à :
At the end of the internship, please return this report via mail or email to:

ENSTA Bretagne – Bureau des stages - 2 rue François Verny - 29806 BREST cedex 9 – FRANCE
☎ 00.33 (0) 2.98.34.87.70 / stages@ensta-bretagne.fr

I - ORGANISME / *HOST ORGANISATION*

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Adresse / *Address* 3317 W. Vine Dr., Fort Collins, CO 80521 USA

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Nom du superviseur / *Name of internship supervisor*
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Fonction / *Function* Professor, Laboratory Director

Adresse e-mail / *E-mail address* Donald.Radford@ColoState.EDU

Nom du stagiaire accueilli / *Name of intern* Gwendal Crequer

II - EVALUATION / *ASSESSMENT*

Veuillez attribuer une note, en encerclant la lettre appropriée, pour chacune des caractéristiques suivantes. Cette note devra se situer entre **A (très bien)** et **F (très faible)**
Please attribute a mark from ***A (excellent)*** *to* ***F (very weak).***

MISSION / *TASK*

- La mission de départ a-t-elle été remplie ? *Was the initial contract carried out to your satisfaction?* — (A) B C D E F
- Manquait-il au stagiaire des connaissances ? *Was the intern lacking skills?* — ☐ oui/*yes* ☒ non/*no*

  Si oui, lesquelles ? / *If so, which skills?* ______

ESPRIT D'EQUIPE / *TEAM SPIRIT*

- Le stagiaire s'est-il bien intégré dans l'organisme d'accueil (disponible, sérieux, s'est adapté au travail en groupe) / *Did the intern easily integrate the host organisation? (flexible, conscientious, adapted to team work)* — (A) B C D E F

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* ______

COMPORTEMENT AU TRAVAIL / *BEHAVIOUR TOWARDS WORK*

Le comportement du stagiaire était-il conforme à vos attentes (Ponctuel, ordonné, respectueux, soucieux de participer et d'acquérir de nouvelles connaissances) ?
Did the intern live up to expectations? (Punctual, methodical, responsive to management instructions, attentive to quality, concerned with acquiring new skills)?

(A) B C D E F

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* ______________________________

____

INITIATIVE – AUTONOMIE / *INITIATIVE – AUTONOMY*

Le stagiaire s'est –il rapidement adapté à de nouvelles situations ? (A) B C D E F
(Proposition de solutions aux problèmes rencontrés, autonomie dans le travail, etc.)

Did the intern adapt well to new situations? (A) B C D E F
(eg. suggested solutions to problems encountered, demonstrated autonomy in his/her job, etc.)

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* ______________________________

____

CULTUREL – COMMUNICATION / *CULTURAL – COMMUNICATION*

Le stagiaire était-il ouvert, d'une manière générale, à la communication ? (A) B C D E F
Was the intern open to listening and expressing himself /herself?

Souhaitez-vous nous faire part d'observations ou suggestions ? / *If you wish to comment or make a suggestion, please do so here* ______________________________

____

OPINION GLOBALE / *OVERALL ASSESSMENT*

❖ La valeur technique du stagiaire était : (A) B C D E F
Please evaluate the technical skills of the intern:

III - PARTENARIAT FUTUR / *FUTURE PARTNERSHIP*

❖ Etes-vous prêt à accueillir un autre stagiaire l'an prochain ?

Would you be willing to host another intern next year? [X] oui/*yes* [ ] non/*no*

Fait à ______________________________, le ____________
In 2024 ______________________________, on ____________

Signature Entreprise ______________________________ Signature stagiaire
Company stamp ______________________________ *Intern's signature*

Merci pour votre coopération
We thank you very much for your cooperation