Optimizing Fabrication and Optical Detection of Battery-Free Colorimetric Leaf Sensors

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Abstract—**Leaf moisture and leaf microenvironment plays an important role in determining overall crop health. Commercial leaf sensors require power supply and are expensive. Colorimetric metasurface-based sensors integrated with moisture-sensitive biopolymers are biodegradable, optical, and battery free sensors that can be detected by ground and aerial robots. In this project, we look at two parts: building a custom tool for low-cost sensor fabrication using nanocrystals, and developing an image processing algorithms to interrogate the optical sensors attached to leaves**.

Index Terms— **Optical sensor, leaf sensor, nano imprint, tool design, image detection**

I. INTRODUCTION

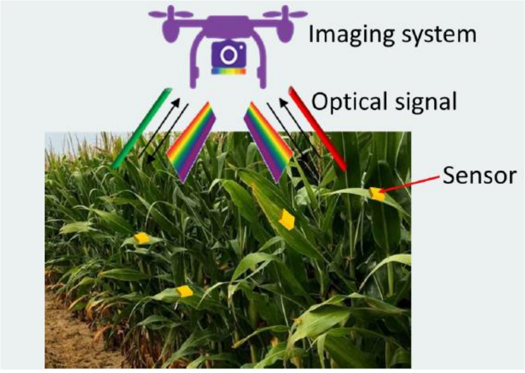


Figure 1: Optical sensor detection using aerial robots.

Agriculture is the nation's backbone and yet it is leading the world in water and fertilizer consumption, accounting for 70 percent of the freshwater withdrawals and 90 percent of its consumption [1]. Current irrigation and fertilization systems over-water and over-fertilize crops leading to wastage and scarcity of these resources. The ability to target specific sections of crops that need these resources will greatly reduce wastage and will improve global food security.

Current remote sensing including hyper-spectral imaging and LiDAR cannot directly measure plant-stress indicators such as leaf moisture, leaf temperature, and soil pH. Remote sensing of these stressors will help isolate them to prevent undesirable outcomes such as low crop yield and crop disease.

Battery-free or passive optical sensors are being deployed to directly monitor plant health at the ground level. These sensors are made with flexible polymers that have nanostructured metasurfaces embedded in them. The ability to fabricate nanostructures in large areas with high precision is crucial to the advancement of passive optical sensors. We explored using nanoimprint lithography with nanocrystal-based inks for its single-step solution-based processing for scalability, low-cost and customizability. There are many constants that need to be considered such as imprint pressure, temperature, humidity, and speed. Current lithography processes are expensive and time-consuming and have a lot of process steps [2].

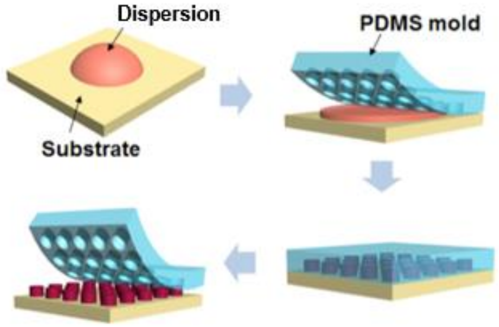


Figure 2: Current nano sensor fabrication process [2].

This paper will discuss a custom tool that will satisfy all the constraints listed above in a more streamlined approach. The custom die set will allow for the user to control the pressure to produce the desired nanostructure geometry. Due to its small size, it can be placed in a humidity chamber to allow for humidity control. An attachment can also be used to control the temperature surrounding the sample to help increase the evaporation of the water that is in the solution.

After the sensors are deployed on the leaves of crops, the next challenge is using aerial and ground robots to detect the color of sensors. The metasurfaces respond differently depending on the immediate dielectric environment, and therefore change color [3]. The main issue is the color of the sensor is slightly different when seen at different angles. In order to account for this, a program was developed using image detection to locate the leaf and stalk of the plant along with a custom camera mount was designed to allow for the RGB camera to pan up and down in order to scan the entire plant along with the ability to scan multiple crops at the same time.

II. METHODS

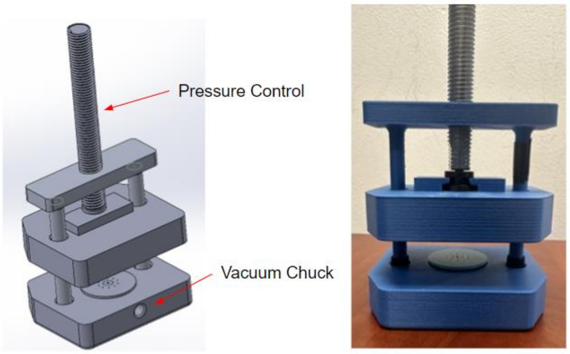
A. *Imprint Tool*

The first step in the design process of the new imprint tool, a list of specifications was created. Table 1 lists the parameters that must be incorporated for each design version, V0 being the current imprint tool, V1 is the first iteration of the design, and V2 being the final design for the imprint tool.

Design Specifications	**V0**	**V1**	**V2**
Fine Pressure Control	✗	✓	✓
Compact	✗	✓	✓
Heating	✗	✗	✓
Vacuum Chuck	✗	✗	✓
Auto Z-Plane Control	✗	✗	✓
Optical Metrology	✗	✗	✓

Table 1: List of the specifications for each imprint tool iteration

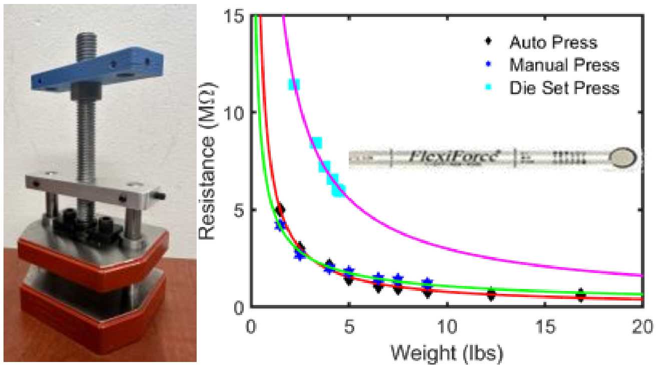
The first iteration design for the custom imprint tool is presented. Shown in Figure 3a is a CAD design of an imprint tool that gives the user continuous pressure control during the imprinting process. The incorporation of an aluminum block on top of the die allowed the user to use the lead screw to actuate the top plate. In order to test if the actuation system worked as designed, the design was 3D printed and tested, as shown in Figure 3b.



(a) (b)

Figure 3(a): CAD design for new die set with a vacuum chuck base. Figure 3(b): 3-D prototype of the die set.

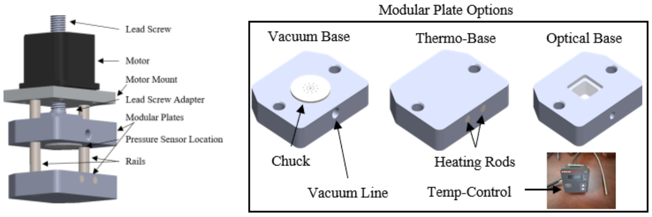
After validating that the design worked as designed, the top block was machined out of aluminum and added to the die set as seen in Figure 4(A). In conjunction with the imprint tool, a pressure sensor was used to ascertain the pressure being applied during the imprint process, see Figure 4b. The force sensor shown in the calibration curve was placed under the substrate during the imprint process and was plugged into a multimeter which displayed a resistance. Utilizing the calibration curve, the pressure was able to be calculated.



(a) (b)

Figure 4(a): Die set with the aluminum block to allow for continuous pressure control Figure 4(b): Calibration curve created for the pressure sensor used during imprint process.

After proving that the V1 design worked, a second iteration of the imprint tool was designed. The V2 design (Figure 5) incorporated the all the specifications listed in Table 1.

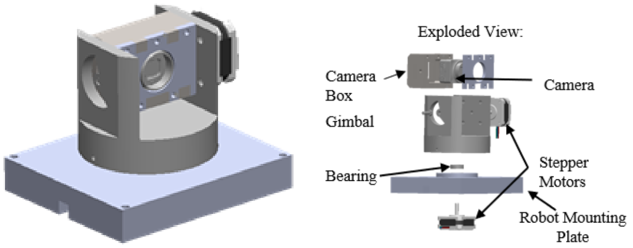


(a) (b)

Figure 5(a): V2 design of the custom imprint tool which incorporates all the specifications listed in Table 1. Figure 5(b): Modular base option for V2 imprint tool design.

B. *Sensor Detection*

The design for the camera mount was first designed in CAD. This design consisted of two stepper motors that rotated the RGB camera in the pitch and yaw direction. This would allow for the camera to scan the entire plant, top to bottom, and pan around to survey the surrounding environment.



(a) (b)

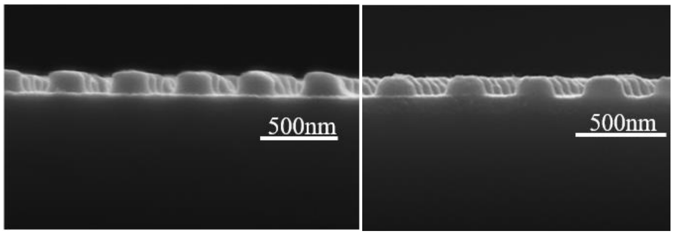
Figure 5(a): CAD design of the custom camera mount. Figure 5(b): Exploded view of the camera mount design.

The second aspect of the sensor detection was to create an algorithm to estimate the angle of the sensor relative to the camera. To accomplish this task, two methods were tested, one was using Hough Line Transforms to estimate the angle of the plant leaf relative to the stalk. The second method was using a shape recognition algorithm to locate the corners of the sensors and estimate the angle based on the side lengths of the sensors.

III. RESULTS

A. *Custom Imprint Tool*

After the V1 prototype was manufactured, a test print was done to check if it was able to produce similar results compared to the V0 imprint tool. After the sensors were made, SEM was done two sensors, one that was fabricated using the V0 (Figure 6(a)) tool and the other from the V1 tool (Figure 6(b)). Both SEMs show similar pillar heights along with pillar spacings which means that the V1 imprint tool was able to achieve similar results as the V0.

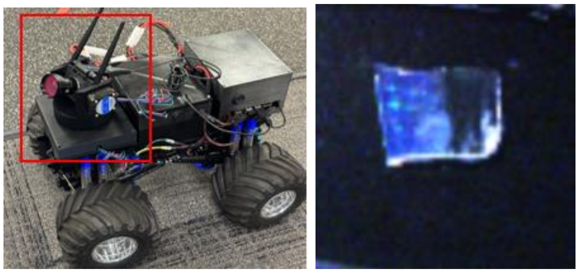


(a) (b)

Figure 6(a): SEM of sensor fabricated using V0 imprint tool. Figure 6(b): SEM of sensor fabricated using V1 imprint tool.

B. *Sensor Detection*

Figure 7(a) shows the 3D printed camera mount on the ground robot being used for sensor detection. This camera mount was attached to the robot and Figure 7(b) is a picture taken with the RGB camera while it was in the camera mount.



(a) (b)

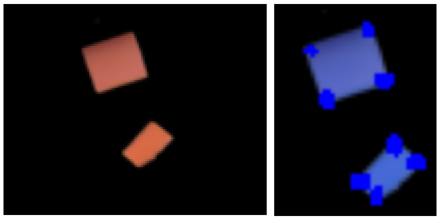
Figure 7(a): Camera mount attached to the robot with RGB camera inside. Figure 7(b): Image of a sensor taken with the RGB camera while in the camera mount.

Figure 8(a-c) shows the image processing used to estimate the angle of the leaf relative to the stalk using Hough Line Transforms.

(a) (b) (c)

Figure 8(a): Original Image. Figure 8(b): Gray scale image. Figure 8(c): Hough Line Transform.

While this process was a success, the sensor has a chance of being located on the part of the leaf that is drooped downwards, so another algorithm was created using shape recognition. This process located the corners of the sensors (Figure 9(b)) and used the side lengths to estimate the sensors using Equation 1.



(a) (b)

Figure 9(a): Image of sensors after being isolated from the leaf. Figure 9(b): Image of corners found using shape recognition algorithm.

$$\theta = cos^{-1}(\frac{x_2 - x_1}{y_2 + y_1})$$

Equation 1: Angle estimation equation using shape recognition. x_1 and x_2 refer to the x-coordinates of the top right and top left corner of the top sensor respectively and the same for y_1 and y_2.

From figure 9(b). It was estimated that the angle of the top sensor relative to the camera was at an angle of 113°.

IV. CONCLUSION

This paper discusses the new imprint tool used for the fabrication of colorimetric sensors. It is shown that the first prototype was able to produce better sensors compared to the current imprint tool being used. A design for the next iteration imprint tool is also provided to further increase the efficiency of the colorimetric sensors.

Along with the new imprint tool design, this paper provided a design of a camera mount for an RGB camera with 2 degrees of freedom, pitch and yaw direction. This allows for the camera to scan a plant top to bottom along with the ability to survey the plants 180° around the robot. The algorithms discussed in this paper is used to calculate the angle of the sensors relative to the camera to allow for the user to understand the true color of the colorimetric sensors.

V. ACKNOWLEDGEMENTS

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