Automating Inspection of Attenuation Grids and Carbon Foils

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Abstract—Crucial to Princeton University's SWAPI (Solar Wind and Pickup Ion) space instrument is the use of an attenuation grid and carbon foil, used to attenuate the intensity of the solar wind and to scatter incoming ions into primary and secondary electrons for detection, respectively. Each of these components' fabrication processes is highly experimental, and defects are common. To ensure that the best grid and foil candidates are flown, an automated inspection system was developed. After considering several system candidates, a controlled stage was chosen, appropriate lighting conditions developed, and algorithms written to mosaic a set of magnified images together and analyze them in a variety of ways.

Keywords—Controlled Stage, Dino-Lite, Attenuation Grid, Carbon Foil, Inspection

INTRODUCTION

Common across many modern space instruments is the usage of ultrathin ($0.5 - 3.5$ $\mu g\ cm^{-2}$ or $\sim 2 - 17$ nm nominal thickness) carbon foils, usually used to detect secondary electron emission resulting from the passage of ions or neutral atoms (McComas et al. (2004)). The SWAPI (Solar Wind and Pickup Ion) instrument being developed by Princeton University's Space Physics Lab utilizes that secondary electron emission to expand the range of detected energies measured by the solar wind, which the instrument will directly interface with. Carbon foils are notoriously difficult to transfer from the glass slide where the carbon is deposited during fabrication to the nickel mesh used to hold the foil in the space instrument; as a result, "foil floating", the method used to transfer the carbon foil between glass slide and nickel mesh, is prone to producing tears and wrinkles in the foil. Any abnormalities like these tears and wrinkles can greatly affect the quality of incoming data on the instrument, as they will directly alter the number of emitted secondary electrons.

In addition to the usage of an ultrathin carbon foil, the SWAPI instrument utilizes a similarly thin component, the attenuation grid, to directly interface with the solar wind, attenuating its intensity by a factor of 1000. The two-layered attenuation grid is comprised of 330,000 holes; the top layer holes ("outer holes") with radii of ~ 35 μm and the bottom layer holes ("inner holes") with radii of between ~ 4 μm and ~ 5 μm. These grids are particularly difficult to fabricate, given the thickness of the material and their two-layered structure. As a result, grids often exhibit "features": stains and blocked or off-center inner holes. These features can affect the consistency of attenuation, thereby putting sensitive detectors within the instrument at risk of overexposure.

Therefore, to ensure that the flight-ready version of SWAPI utilizes the best possible attenuation grid and carbon foil, grid and foil candidates must be inspected and compared. This, however, is also a particularly difficult process, as an attenuation grid with 330,000 holes is nearly impossible to quantitatively evaluate, much less compare with other candidates. For this reason, it is essential to develop an automated inspection system capable of evaluating the flight-readiness of each grid and foil candidate, thereby assisting in the selection of which grid and foil will be used in the flight-ready version of SWAPI.

INSPECTION SYSTEM CANDIDATES

In brainstorming potential systems to be used for grid and foil inspection, a collection of crucial features were identified: ease of reproducibility, ability to resolve both outer and inner holes as well as inner hole offset and blockage, ability to operate system in a cleanroom environment, and rapid system implementation. The following three systems were considered.

Single, High-Resolution Image with Digital Camera

Evaluating the feasibility of the simplest model first, the first attempt at inspection was performed with a digital camera. The setup was as follows: a long, cardboard tube was placed over the lens of a Canon DSLR camera, its length corresponding roughly to the focal length of the lens at its current magnification. Aluminum foil coated in matte black paint was wrapped around the end of the tube, a rectangle cut from the center to attach the plastic that the attenuation grid was statically adhered to. Finally, a flashlight was directed at an angle through the attenuation grid, thereby providing a backlight for the grid (Fig. 1).

The first image taken (Fig. 2) with the setup proved fruitful for establishing the most effective setup; while numerous ar-

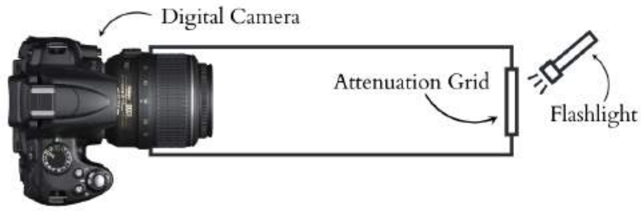

Fig. 1: Digital camera inspection setup.

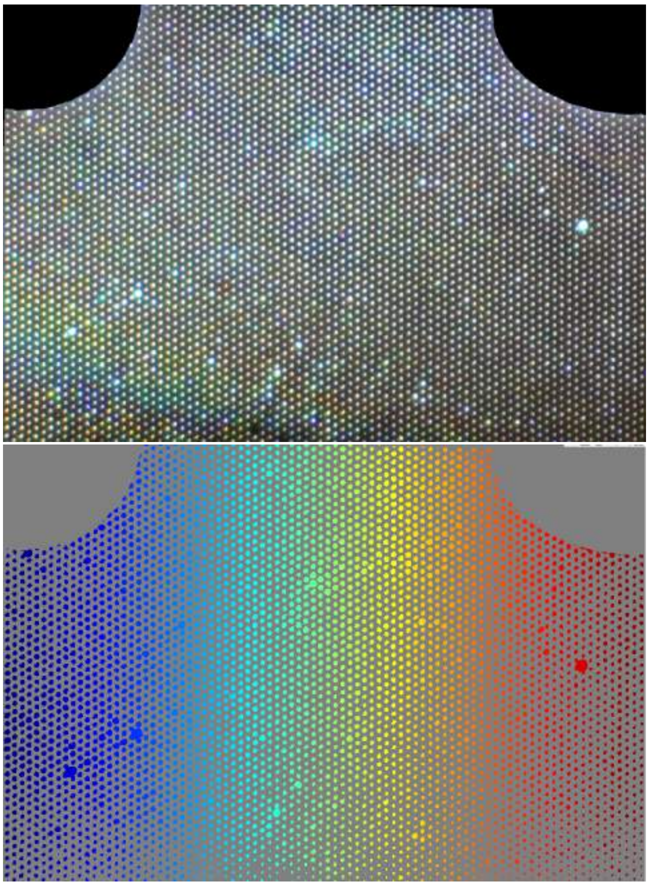

Fig. 2: First image taken with digital camera setup, raw (top) and processed (bottom).

tifacts were created as a result of the rapid prototyping of the system like the diffraction gradient at the bottom left corner, the image resolution allowed preliminary outer hole identification to be performed (Fig. 2). This identification allowed both missing holes and abnormally large holes to be identified, but crucially, inner holes could not be resolved with the method. We hypothesized that other reasonably priced lens would yield similar results. As a result of this limitation, other setups were investigated with the express hope of resolving inner holes and their offsets.

Repurposed 3D Printer + Dino-Lite Microscope

The next clear option was to utilize the lab's Dino-Lite digital microscope to inspect the grid or foil with significantly greater magnification. After conducting several small experiments, we concluded that the entirety of the attenuation grid could not be captured with reasonable resolution using the Dino-Lite, so an image mosaic would need to be constructed. As a proof of concept, the Dino-Lite was translated by hand to capture mosaic images, but unsurprisingly, it proved tenuous considering the magnification.

To address the issue of consistent mosaic images, the second approach was theorized: repurpose a 3D printer controlled stage by removing its fans, extruder, and bed heater, design a holster for the Dino-Lite to be attached to the controlled stage, and write g-code to scan across the inspection region. The scan would be programmed such that the stage would move between image positions with pause time between each motion, giving the Dino-Lite the ability to settle and capture an image. Depending on whether the firmware of the chosen 3D printer was open- or closed-source, the control board could be replaced with an Arduino and RAMPS board so that new firmware could be written and modified.

Despite putting considerable effort into developing this approach, the final criteria for the system, rapid system implementation, could not be met. Therefore, another approach with shorter development time would need to be considered.

Dino-Lite VisionM4 Controlled Stage

Given those considerations, the next step was to explore premade controlled stage options. Conveniently, the brand of the lab's microscope also offered a controlled stage. In fact, it offered exactly what the second approach hoped to accomplish: programmable motion, a holster designed to hold the Dino-Lite, a cleanable mechanism (for use in a cleanroom environment), and seamless coordination between the Dino-Lite and the controlled stage. Despite a hefty price tag, this approach appeared to be the most likely to succeed, so the system was purchased and implemented.

After receiving and assembling the controlled stage, the majority of the setup was completed, the primary remaining obstacles being the lighting setup and software development.

DEVELOPING LIGHTING CONDITIONS

Considering the scale at which the Dino-Lite operate and the reflectivity of the material, proper lighting conditions have been proven crucial to properly recognizing small and large holes. More specifically, certain combinations of foreground and background lighting ensure that holes are nearly indistinguishable from the broader surface or that the inner holes are not well lit enough to detect. To address these issues systematically, the background and foreground lighting conditions were developed independently from one another.

Foreground Lighting

Upon conducting several small lighting experiments, we determined that there were two primary considerations for foreground lighting conditions: uniformity and intensity. The first lighting source test was conducted with a flashlight pointing directly down onto the grid, at an angle toward the grid, and parallel to the grid. Each of these setups proved problematic for image mosaicking efforts as a result of the non-uniformity of the lighting (Fig. 3).

The next source was the LED on the Dino-Lite itself; the LED is comprised of a series of 10 smaller bulbs in a ring around the lens of the microscope. Considering the non-uniformity of the raw lighting of those bulbs, the microscope also includes several diffuser caps. After capturing images with the Dino-Lite LED at varying intensities (Fig. 4), the lowest nonzero intensity was chosen, as it emphasizes inner holes but leaves outer holes resolvable. This selection has been utilized for all other attenuation grid analyses.

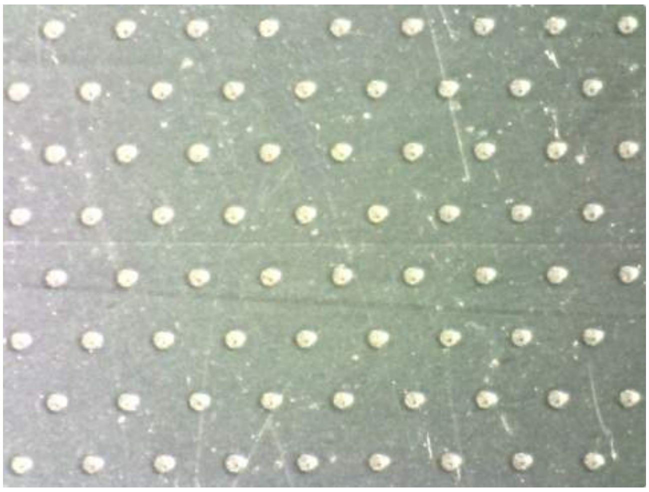

Fig. 3: Lighting test conducted with Dino-Lite and flashlight pointing downward at an angle toward attenuation grid.

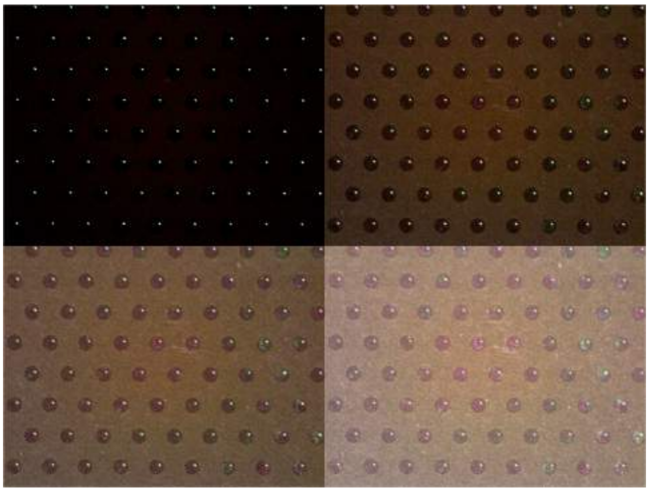

Fig. 4: Lighting test with varying Dino-Lite LED intensities.

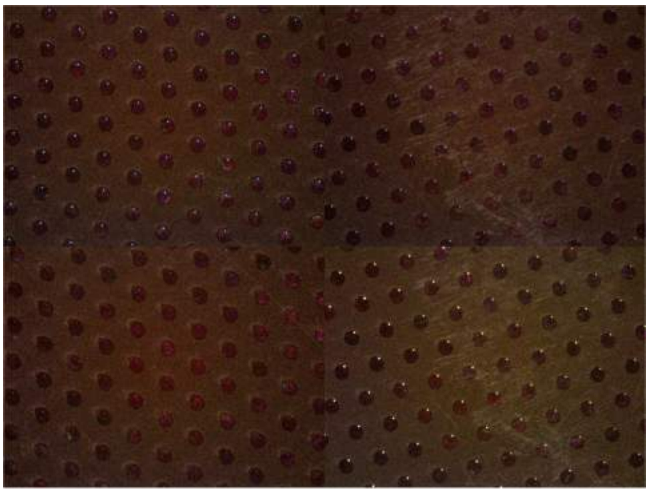

Fig. 5: Lighting test with varying backlight colors.

A similar lighting intensity test was conducted with the carbon foil; given the results, we concluded that no foreground lighting was necessary.

Background Lighting

Since attenuation grids are designed to attenuate the intensity of incoming light by a factor of 1000, it proved necessary to choose the most intense setting of whatever backlight was being tested; therefore, the primary consideration became whether or not to color the incoming backlight. Doing so can change the contrast between inner and outer hole, as well as offer the ability to filter the image by red, green, or blue band during the image processing stage. To best determine the choice of color, images were taken with several different acetate gels between an LED panel serving as the backlight and the attenuation grid (Fig. 5). Given the potential of band filtering, red was chosen since it fell purely in the red band, where the blue exhibited blue tint. Therefore, in sum, all future attenuation grid analyses have been conducted with an LED panel backlight at full brightness with a red acetate gel between it and the attenuation grid. Foreground lighting is provided by the Dino-Lite LED at the lowest nonzero setting.

A similar lighting color test was conducted with the carbon foil; given the results, we concluded that no color was necessary. Therefore, in sum, all future carbon foil analyses have been conducted with an LED panel backlight at full brightness, no acetate gel, and no foreground lighting.

DEVELOPING MOSAICKING ALGORITHM

The primary challenge of developing this system was bound to be the image mosaicking, given the shear number of images ($\sim$ 1200 images for attenuation grids and $\sim$ 100 images for carbon foils), as well as the importance of a good fit – blurry image overlays invalidate analyses of inner hole offset and outer hole size. With those components in mind, two approaches were developed in Matlab, as their image processing toolkit is significantly more robust than that offered by Python.

Centroid-Based Mosaicking

The first assumption made when considering mosaicking algorithms was that images must be *standardized* in their cropping, rotation, and magnification. The idea was that, if all images were of an identical format (not a safe assumption, in retrospect), then mosaicking could be performed in a highly mechanical way. Therefore, much effort was expended into developing an automatic rotation correction algorithm – several transforms were tested, but a radon transform was decided upon – and hole fitting to allow for automatic cropping. The holes were then assigned a "centroid", which provided a center and effective radius, which would be used to calculate each boundary cutoff.

This algorithm was effective for high quality images with few features and whose rows were exactly parallel to the motion of the controlled stage bed. Images that did not meet those criteria suffered exponentially-worsening fits as the scans scaled. Therefore, to ensure robustness, a new algorithm was formulated which made far fewer assumptions about the grid, its orientation, and the quality of the images.

Spacing-Based Mosaicking

The fundamental requirement of the spacing-based mosaicking algorithm is an approximate understanding of the uncertainty within the steps of the stepper motors of the controlled stage. Since the expected spacing between images can be calculated by the number of images in a row or column and the physical size of the field of view, a range of potential horizontal and vertical spacing can be determined. The gray scale difference between overlapping images can be calculated for several values within each spacing range and an extrema can be identified which minimizes the mean value of the overlap (which, in turn, represents the amount of blurriness to the fit). The algorithm forms entire rows first and then appends rows together using a similar method. This approach relies on nonzero brightness fluctuations within a given image (which will result from holes, features, or even nonuniform plain surfaces), but does not make any assumptions about the presence or orientation of holes. The only requirement of the spacing-based algorithm is the alignment of the Dino-Lite field of view and the movement of the bed, which is far easier to accomplish than alignment of the grid with the movement of the bed. Therefore, moving forward, a spacing-based mosaicking algorithm has been used to produce both attenuation grid and carbon foil mosaics 6.

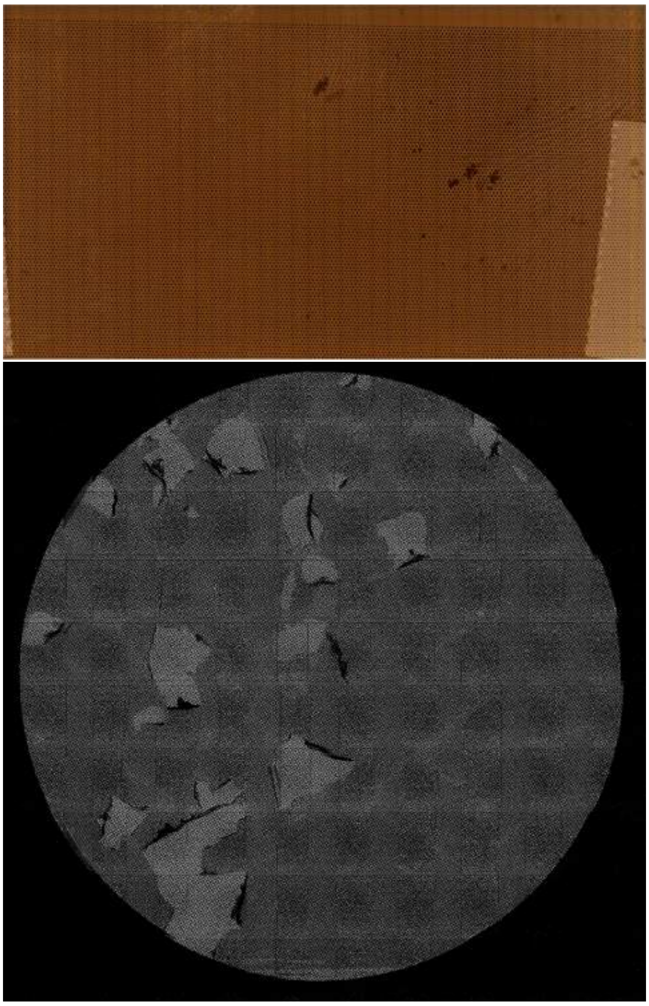

Fig. 6: Full color image mosaics, brightened for visibility (attenuation grid above, foil below).

ATTENUATION GRID ANALYSIS METHODS

At a fundamental level, acquiring the positions and effective radii of both the outer and inner holes is sufficient for any of the analyses described above; so, the foremost task was developing an image binarization algorithm to generate a mask of both holes and features. With the help of Matlab's `imbinarize` function and several others from the image processing toolbox, a threshold-based algorithm was developed both to distinguish outer holes from everything else, and inner holes from everything else, provided the blue and green bands were subtracted from the red band to provide the clearest view of inner holes. Once two binary masks were generated, another function from the image processing toolbox, `regionprops`, was used to identify each connected region as a centroid with a center and an effective radius. Together, those data have been proven sufficient for conducting the remaining analyses.

Blocked Hole Distribution Scatter Histogram

The first objective of the analysis was to identify "dead spots", or clusters of blocked holes, in which case, the blocked holes themselves would have to first be identified. To do so, the blocked hole finding algorithm loops through the list of outer hole centroids and checks if there exists an inner hole whose center lies within the radius of the outer hole. If no inner hole meets that condition, the outer hole is flagged as blocked. That list of blocked holes is then plotted in a scatter histogram (Fig. 7).

Offset Distribution Colormap

The second objective was to quantify inner hole offset. To achieve this, all connected regions identified by `regionprops` that are not identified by the blocked hole identifying algorithm, or the "good holes", are flagged and corresponding inner and outer holes are placed into an array. Next, the distance between each center is plotted via colormap to identify regions of high and low inner hole offset (Fig. 8).

CARBON FOIL ANALYSIS METHODS

Fused Tear Overlay

The final objective was to identify tears and wrinkles in carbon foils. To do so, a similar operation as with attenuation grids (using the `imbinarize` function) is performed on the carbon foil in two steps. The first step, producing a binary mask which identifies the boundary of the foil within its frame, and the second step, producing a binary mask which identifies the tears within the valid boundary, are combined to create one mask representing "effective area". That effective area mask is then overlaid with the original image to create a visualization of tears (Fig. 9) which can be compared and contrasted after conducting experiments on the foil.

FUTURE WORK

The majority of potential algorithm enhancements have been reserved for future work, purely as a result of lack of time.

First, algorithm efficiency could be dramatically improved

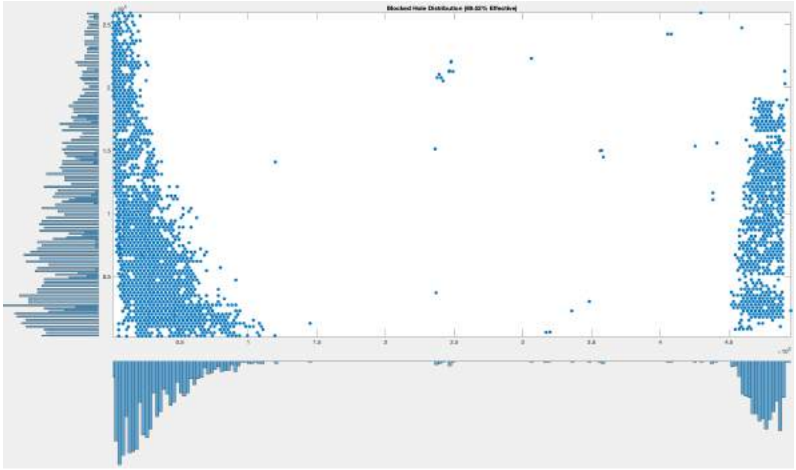

Fig. 7: Blocked hole distribution scatter histogram.

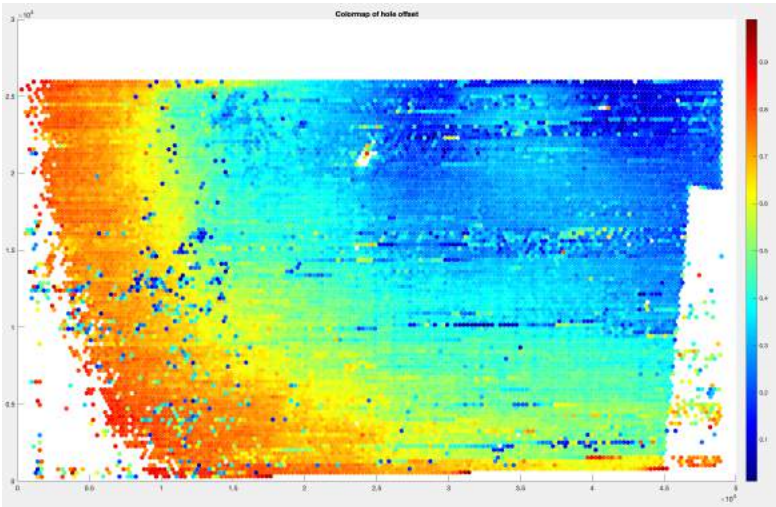

Fig. 8: Blocked hole distribution scatter histogram. Blue coloring represents low inner hole offset, while red coloring represents high inner hole offset.

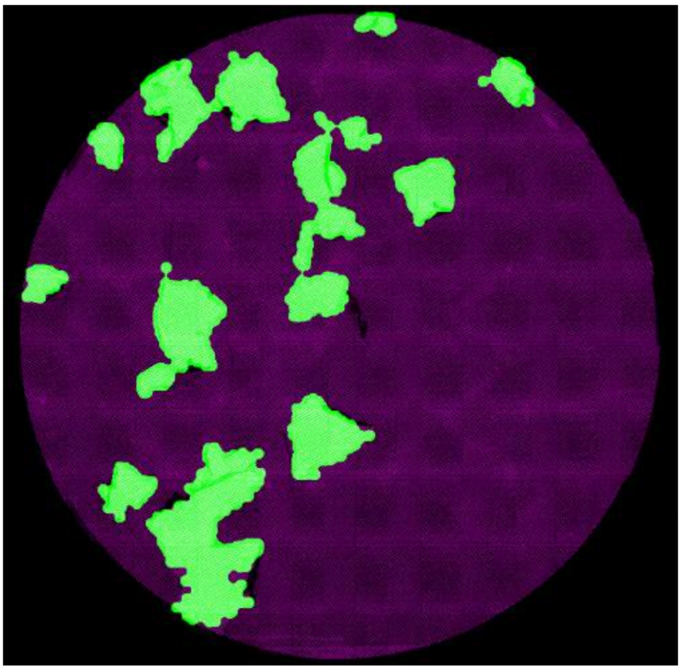

Fig. 9: Torn region overlay. Green coloring represents torn regions.

by relying less on Matlab's image processing toolbox and instead writing more specific algorithms that only accomplish what is needed – currently, attenuation grid mosaics take approximately 20 minutes to run on a stock 2020 Macbook Pro; further analyses take another 30-40 minutes to run.

Next, the algorithms themselves – primarily the image mosaicking algorithm – could be modified to produce more consistent results. Currently, the algorithm requires several inputs to be provided, including the horizontal spacing and vertical spacing intervals. These intervals are particularly difficult to choose, as they do not seem to correspond exactly with what you would expect from the physical size of the field of view, the step size, and the uncertainty in the steppers. Rather, they tend to be offset from the expected range by a few hundred pixels in either direction. Additionally, even when the proper parameters are identified, they tend to be a best fit only to the majority of images, leaving some regions of the grid or foil poorly fit. Poorly fit holes, for example, can invalidate both the offset distribution colormap or even the blocked hole distribution scatter histogram, depending on the level of offset.

Finally, throughout the final few days of the project, the controlled stage was moved to the cleanroom, where it will operate long-term. Interestingly, we observed that approximately 10% of the captured images, randomly distributed, were completed blurred along the horizontal axis. Despite investigating several potential causes like excessive air flow caused by clean room HEPA filters, table bumps by the curtain surround the clean room, and too short rest times between movements, the culprit is yet to be identified as of writing this paper. To continue with effective analyses, this issue must first be resolved.

CONCLUSIONS

In this paper, we addressed the problem of inspecting attenuation grids and ultrathin carbon foils for use in the SWAPI instrument. In particular, we discussed the considered approaches for imaging each component, their benefits and limitations, and highlighted the selected controlled stage from Dino-Lite. Next, we emphasized the framework necessary to conduct a reliable analysis, including the development of effective lighting conditions and an image mosaicking algorithm. Finally, we described three analyses performed on grids and foils, as well as potential future work. Our initial objectives were to develop a system capable of grid and foil inspection with ease of reproducibility, the ability to resolve both outer and inner holes as well as inner hole offset and blockage, the ability to operate the system in a cleanroom environment, and rapid system implementation. Considering the discussion above and the eight-week timeline, we have achieved these objectives.

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