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An automated damage inspection microscopy system for National Ignition Facility optics

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An automated damage inspection microscopy system for National Ignition Facility optics

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ABSTRACT

Identifying laser induced damage on the surface of optical components for the purpose of tracking its growth over time and repairing it is an important part of the economical operation of the National Ignition Facility (NIF). Optics installed on NIF are monitored in situ for damage growth and can be removed as needed for repair and re-use. An *ex-situ* automated microscopy system is used to inspect full sized NIF optics allowing for the detection of damage sites >10 µm in diameter. Due to the various morphology of laser damage, several algorithms are used to analyze the microscopy data and identify damage regardless of size, while ignoring features not related to laser damage. This system has significantly increased the lifetime of NIF final optics (∼2.3x) thereby extending beyond the capabilities of the *in-situ* inspection by itself.

1. INTRODUCTION

The National Ignition Facility (NIF), routinely delivers up to 1.9 MJ of 351nm light. Operation at these energies requires that the system routinely operate at fluences well above the growth threshold of its final fused silica optics.[1] The routine and sustained operation of the 192-beam NIF laser is enabled through the use of an optics recycle loop,[2] wherein optics are monitored, removed, repaired, and reused on the NIF laser. A key element of NIF's recycle loop is an *in situ* optical inspection system which determines when the accumulated laser damage on each optic's surface exceeds the allowed value and requires its removal from the system.[3] At the time of removal a damaged optic is replaced by either a new or recycled optic, whose damage sites have been mitigated (repaired).[2] Damaged optics are taken to a lab where individual damage sites are repaired using a CO_2 laser which ablates material from each damage site, removing any fractured material and, leaving a conical mitigation (repair) site in its place.[4]

Small (<50 µm) damage sites, which can not reliably be identified using NIF's *in situ* inspection system, have a significant chance of growing with subsequent, high fluence, laser exposure.[5–7] To maximize the installed life of each component it is, therefore, advantageous to identify and repair both the sites observable with the *in situ* inspection system, as well as the larger number of small (<50 µm) sites which cannot reliably be detected using NIF's *in situ* inspections. To reliably detect and determine the size and location of both large and small damage, each optic is scanned over their entire (43x43cm) aperture using a Nikon Model VMZ-R 6555 automated inspection microscope.

This paper describes the requirements, implementation, and performance of an automated system which has been built to allow the acquisition and autonomous classification of defects from high-resolution imagery of full aperture NIF fused silica surfaces as needed to support NIF's optics recycle loop. Specifically, we describe the use of algorithms that are used to locate the position, size and type of feature detected on NIF large optics. Once detected, a series of machine learning based methods are used to differentiate between various features, including damage sites, previously repaired damage sites, and other types of feature such as extraneous debris. Since the vast majority (>95%) of damage sites occur on the exit surface,[8,9] to maximize the capacity of the recycle loop, only the exit surface of each optic is scanned. Nonetheless, the small fraction of input surface damage sites, which have the potential to grow during subsequent laser shots(even if at a substantially reduced rate[10]), can limit the useful life of the components. Therefore, we also describe the development and performance of an algorithm that is used to detect and classify out-of-focus sites originating on the input surface of NIF optics.

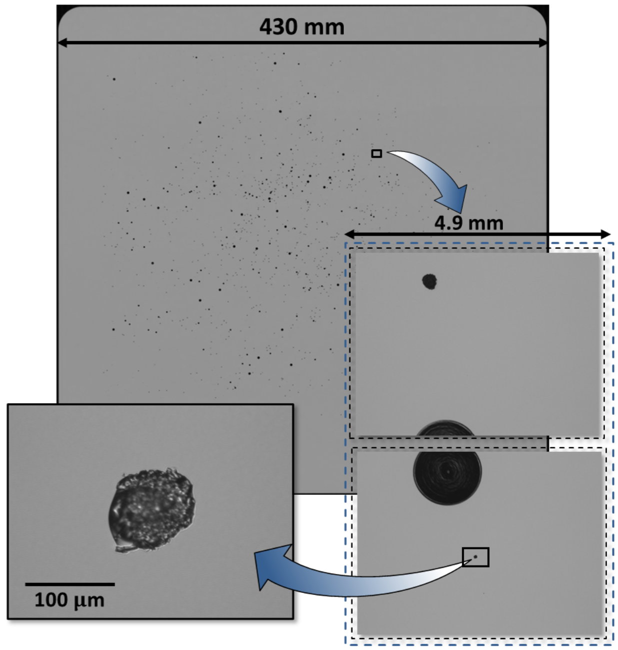

Figure 1: A NIF large optic montage composed of ∼10,000 individual images, each with a 4.9mm field of view. Lower left shows a high-resolution image captured of detected damage site during an automated scan.

2. AUTOMATED SYSTEM OVERVIEW

The automated damage inspection microscopy system (ADIM) is capable of identifying all damage greater than 10 µm on a full aperture NIF optic. An initial montage of a full large optic is captured consisting of ∼10,000 individual micrographs (∼7 GB of data). Each image has a resolution of 4.5 µm per pixel and can be stitched together to form a high resolution image of the surface of each full aperture optic as shown in Figure 1. Images are analyzed independently, identifying all features greater than 10 µm on the top (laser exit) surface and 50 µm on the reverse (laser entrance) surface, with any features crossing image boundaries being merged. Large (>∼100 µm) damage is identified from the full optic montage, while smaller damage is identified after additional high-resolution (∼0.33 µm per pixel) microscopy.

Several subsystems are used to identify features on both surfaces of each optic and classify each feature to determine if repair necessary. Features are initially identified from an initial full optic scan. ADIM is capable of identifying all features greater than 10 µm on the optic exit surface and greater than 50 µm on the input surface. Any previously repaired damage is identified to validate placement and to check for any failing repairs. Finally, each feature is classified; features smaller than ∼100 µm have individual high-resolution micrographs captured for classification, while large features are classified from the initial large optic scan. Any identified damage is then reported so it can be subsequently repaired.

2.1 Feature Detection and Merging

Laser induced damage on NIF large optics can range in size between a few microns and a few millimeters. Due to the wide disparity in damage site sizes, two feature detection methods are employed. Large (>∼100 µm) features are found by first computing a prototypical background by fitting a polynomial surface to an empty set of images. The prototypical background is used to flatten each image and large features are found by thresholding each flattened image. This method reliably finds all large features greater than 100 µm. Small features are identified using the local area signal to noise ratio (LASNR) method.[11]

Due to the limited field of view of any given micrograph during the full optic scan, features are regularly contained in multiple images. If analyzed naively, any feature partially captured by N frames will subsequently be identified as N independent defects with each individual feature "fragment" being incorrectly sized. This

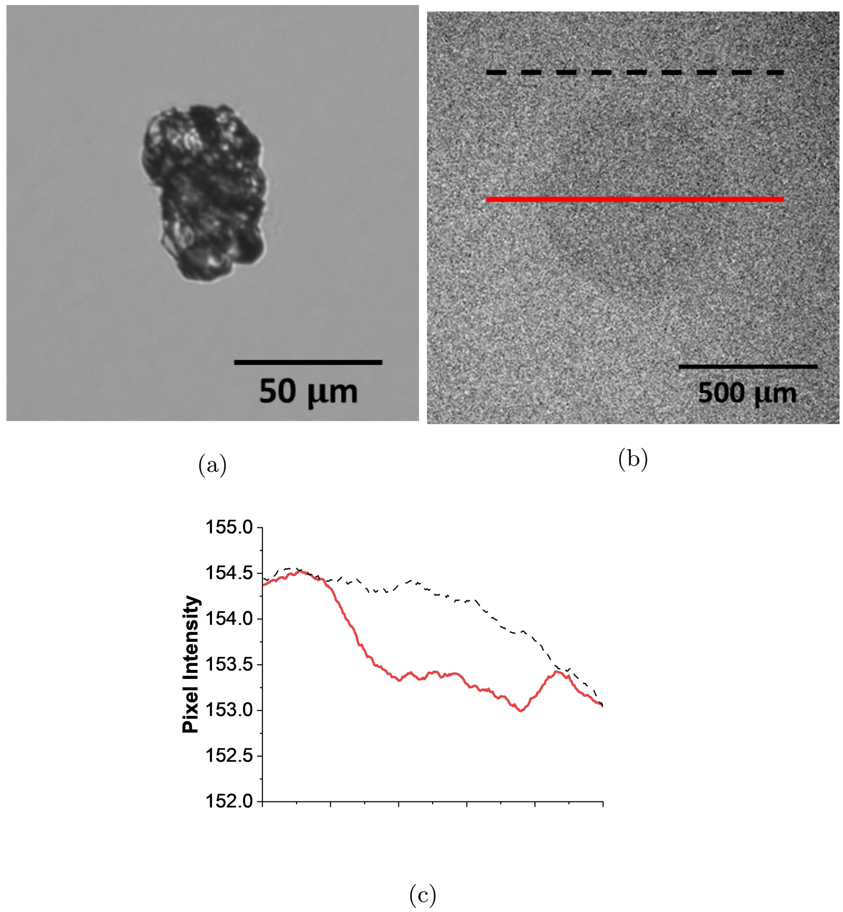

Figure 2: (a) A typical 50 µm input surface damage site on a NIF GDS. (b) Contrast enhanced out-of-focus obscuration from (a) while focused on GDS exit surface. (c) Intensity profile of corresponding lines in (b).

could of course be circumvented by composing a full optic montage of an optic before performing any analysis, but this would be unacceptably slow. ADIM independently analyzes each image independently. Any feature identified is compared with features found in other images to check for an overlap, and if any overlap is found the features are merged. This enables parallel microscopy image analysis while still accurately sizing features fragmented into multiple images.

2.2 Out-of-Focus Feature Detection

As discussed above, laser damage on NIF final optics predominantly occurs on the exit surface,[8,9] but does occasionally occur on the input surface. Therefore, the detection and identification of input surface damage sites is necessary to ensure comprehensive repair of each optic. However, due to the slower growth rate of input surface damage sites,[10] it is only necessary to identify input sites >50 µm. ADIM therefore uses information from the full optic exit surface scan to identify the location of potential input surface sites. Any identified input surface sites can later be specifically imaged without requiring the full input surface of the optic to be scanned. Features on the input surface are ∼1 cm out-of-focus, while the microscope depth of focus is ∼10 µm, and there features are treated as point obscurations. As seen in Figure 2, a 50 µm obscuration is quite faint when viewed from an exit surface scan, but does deviate significantly from the local background.

Template matching is used to create a map of regions that most closely resemble an out-of-focus obscuration using an empirically derived template of a small damage site.[12] Highly correlated regions (defined by a threshold) are found. To minimize the number of unidentified input features by template matching, the threshold is set intentionally low. Due to the low threshold, falsely detected input surface features are

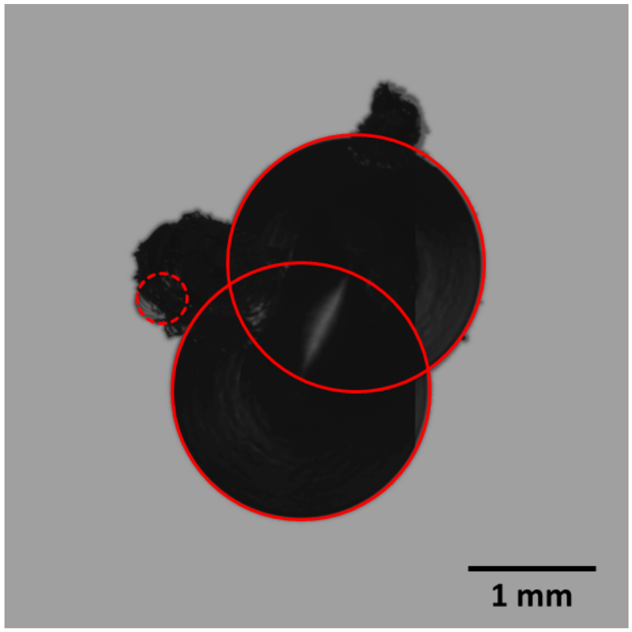

Figure 3: Two NIF repair cones with multiple failures. Solid red circles indicate correctly identified previously applied repairs. The dashed red circle represents a false detection by the repair finding system that will later be identified and treated as damage.

regularly found. ADIM attempts to identify false detections; measurements of potential detections are collected, and an ensemble of decision trees is used to determine the if a potential detection is real.[13]

2.3 Repair Identification

As NIF optics are recycled multiple times, previously repaired sites are commonly imaged during a large optic scan. As seen in Figure 3, repairs can be joined with other repairs to form complex structures, as well as become damaged requiring additional mitigation. A Hough circle transform, with predefined radii based on protocol sizes, is used to identify potential locations of previous repairs. To limit transform time, Hough space is only found in regions inside a given feature. An ensemble of decision trees is used to eliminate any falsely detected repairs, such as damage with concentric fractures with a radius of curvature similar to a repair protocol. First, any detected repairs are used to validate the location of repairs. Second, detected repairs are as information for subsequent feature classification.

2.4 Defect Classification

Features are classified into into one of four classifications: "Damage", "Repair", "Damaged-Repair", or "Non-Damage". "Damage" (pictured in the bottom left of Figure 1) typically varies between 10 and 400 µm in size. "Non-Damage" generally consists of either debris that has fallen on the optic surface or etched scratches. "Repairs" and "Damaged-Repairs" vary widely in size (occasionally upwards of 3 millimeters), but are never below ∼200 µm in size. Any "Damage" or "Damaged-Repair" can be marked for subsequent repair, while any "Repair" or "Non-Damage" has its location recorded, but is ignored. Two independent systems are used to classify features, dependent on the size of the feature.

Large (greater than 100 µm) detections are classified using a hybrid classifier,[14] consisting of a resnet-18 feature extractor and an ensemble of decision tree classifier.[13,15,16] A three-channel image is made consisting of a montaged micrograph of the feature, a binary mask of any repairs identified by ADIM, and a binary mask of any recorded repair locations. As seen in Table 1, the large feature classifier is highly sensitive to both to "Damage" and "Damaged-Repair" classifications accurately identifying ∼99% of all damage in a test set. Misclassified features generally do not result in a failure to repair damage and therefore do not impact the results of ADIM.

		Truth			
		Damage	Repair	Damaged Repair	Non-Damage
Prediction	Damage	2891	14	12	21
	Repair	0	5075	43	17
	Damaged-Repair	0	726	1317	10
	Non-Damage	0	56	0	288

Table 1: Confusion matrix of the ADIM large (greater than 100 µm) feature classifier.

Small (less than 100 µm) sites are classified with high-resolution (∼0.33 µm/pixel) micrographs centered on the feature of interest and a resnet-18.[15,16] The resnet model was trained using transfer learning and ∼40,000 individual features that were hand labeled. Micrographs using three distinct lightings are captured of each feature: transmitted light, reflected light, and an oblique angle darkfield lighting. Table 2 shows the confusion matrix of the small site ADIM classifier. This classifier is capable if accurately identifying over 99% of damage from a test set and ∼99% of "Non-Damage" features. "Repair" and "Damaged Repair" features are not present in this confusion matrix as all repairs are greater than 100 µm in size and are therefore never classified by this classifier.

		Truth	
		Damage	Non-Damage
Prediction	Damage	7023	45
	Non-Damage	40	3977

Table 2: Confusion matrix of the ADIM small (less than 100 µm) feature classifier.

3. CONCLUSION

Damaged NIF final optics are regularly removed, inspected, and repaired before being reinstalled for further use. To maximize each optic's installation period, an automated microscopy inspection and analysis system has been developed to identify all damage greater than 10 µm on an optic's exit surface. The system has the capability of scanning and analyzing an entire NIF large optic (∼43x43 cm) in 4 hours. Each scan has a resolution of ∼5 µm per pixel. Sites are first detected on both surfaces utilizing a backlit full optics scan. Secondly, previously repaired damage sites are identified to aid subsequent classification. Finally, each candidate site is classified and damage is identified so that it can be appropriately repaired.

ACKNOWLEDGMENTS

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