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# PATH TO IGNITION AT THE NATIONAL IGNITION FACILITY(NIF): THE ROLE OF THE AUTOMATIC ALIGNMENT SYSYEM

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*Abstract*

The historical breakthrough experiment at the National Ignition Facility (NIF) produced fusion ignition in a laboratory for the first time and made headlines around the world. This achievement was the result of decades of research, thousands of people, and hardware and software systems that rivaled the complexity of anything built before. The NIF laser Automatic Alignment (AA) system has played a major role in this accomplishment. Each high yield shot in the NIF laser system requires all 192 laser beams to arrive at the target within 30 picoseconds and be aligned within 50 microns-half the diameter of human hair-all with the correct wavelength and energy. AA makes it possible to align and fire the 192 NIF laser beams efficiently and reliably several times a day. AA is built on multiple layers of complex calculations and algorithms that implement data and image analysis to position optical devices in the beam path in a highly accurate and repeatable manner through the controlled movement of about 66,000 control points. The system was designed to have minimum or no human intervention. This paper will describe AA's evolution, its role in ignition, and future modernization.

## INTRODUCTION

On December 5th, 2022, a long sought-after and challenging milestone was achieved within the NIF facility at Lawrence Livermore National Laboratory [1, 2] by successfully producing fusion ignition for the first time. This important accomplishment enables a path towards solving countless national and world problems including the ability to provide abundant, clean energy for generations to come. The automated alignment system [3, 4] is a vital part of NIF and provided major contributions towards this achievement.


Figure 1: On December 5th, 2022, fusion ignition was achieved within the NIF facility at Lawrence Livermore National Laboratory. Imploding target within the hohlraum is depicted on the right.

Inside the NIF facility during what is called a shot, all 192 lasers are amplified, conditioned, aligned, and focused on their path to finally enter the hohlraum at the target chamber center, (Fig. 1) This generates X-rays that cause the target capsule (Fig. 2) within to implode that cause the deuterium and tritium atoms inside to fuse. As a result, ionized helium nuclei (alpha particles) are released into the surrounding fuel, and their deposited kinetic energy results in rapid heating of the surrounding fuel which causes a cascade of fusion events known as ignition when the deposited energy overcomes energy loss processes in the imploding fuel. The initial spark of fusion in the imploded hot spot needs to be sufficiently strong to cause ignition, and a higher temperature hot spot can increase the initial fusion spark [5].

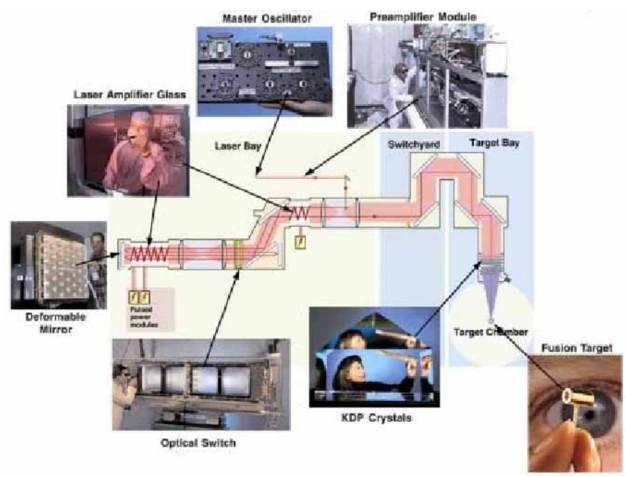


Figure 2: Schematic representation of a NIF laser beam line highlighting some of the key technologies.

The success of a fusion shot is contingent on precision alignment of 192 laser beams towards the target by moving thousands of optical and electro-mechanical components under the control of the AA system. The AA system is a data driven software framework with the ability to position optical and mechanical devices and align 192 high power laser beams accurately and consistently with minimal or no human interaction. To accomplish this, AA provides automated execution of multiple layers or loops of complex algorithms using data and image analysis which will be described in the following sections.

## AUTOMATIC ALIGNMENT STRUCTURE

NIF AA is a data driven software framework to set up the devices at correct positions and align 192 laser beams accurately and consistently with minimum or no human

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interaction in timely manner. NIF AA also has a sophisticated user interface built on multiple layers, complex algorithms, a testing framework and a maintenance and commissioning toolset.

AA can be viewed as having 6 main components: segment managers, database retrieval, component mediation system (CMS), loops, image processing, and data analysis. Each Segment Manager and CMS run on different servers and has the capability of running independently. The components are built to manage the optics, devices and processes required for laser alignment. The entire process sets up devices and manages motors to precisely move the position of the optics. Main components and process flow can be seen in Fig. 3. A description of each component follows.

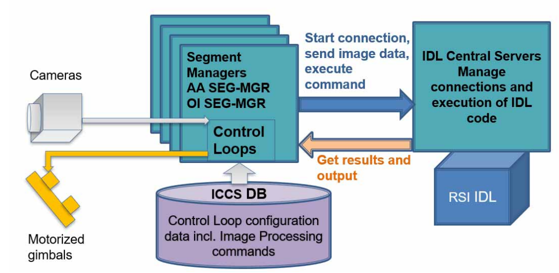


Figure 3: Automatic alignment architecture diagram.

## *Segment Manager*

The segment managers in (Fig. 4) occupy the topmost layer in the AA architecture and orchestrate all commands and devices in AA alignment. Each layer can be processed, is run independently, and contains a list of child segment managers which are separated as per the area in each respective laser path. Each child segment manager controls its own set of segment commands. Each segment command contains a sequence of controls that consists of CMSs and Loops. This architecture offers a practical way to control and guide the laser in real-time and in different stages. The CMSs and loops are sharable within the same segment manager. Segment commands use measurement and characterization techniques and are designed to run in parallel across the beams while taking care of the shared devices.

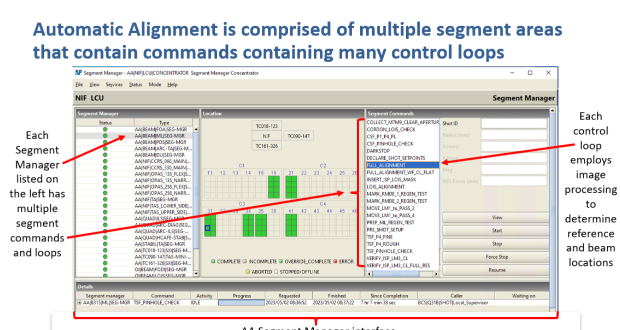


Figure 4: Segment Manager User Interface.

## *Database Retrieval*

The position of the motors for the best laser alignment is recorded at every point in the alignment process. Data from selected prior experiments is used to set the initial position of devices for each shot to ensure that expected beam intensity and wavelength is optimized. The data from the database includes the execution plan to run the entire alignment, the initial positions of the devices that is required for the process to run, loop configuration data, image processing commands.

## *Component Mediation System (CMS)*

CMS contains cluster of configurations for mediation systems. Each CMS configuration manages a set of devices for its positioning or tracking the devices position at “At Position”, “GoTo Position” or “Reserve”. Shared devices are managed using reservations.

## *Loops*

Each Loop is a process to capture sensor data, usually camera images that identify fiducials or beam features in the image. The resulting analysis is used to position devices and optics. There are more than 600 loops that provide specialized requirements for each laser area. All loops are assigned a camera, a gimbal and CMS configuration based on its type. When the loop starts the assigned CMS configuration, it sets up the assigned devices in the beam path to the planned positions. To achieve the desired results the loop iterates and goes through the process in moving the Gimbal, capturing the beam on the camera, and sending the images for image processing. The loop has a finite number of iterations and stops running when the laser centroid position is found within a specified tolerance. All AA loop data including images is saved to the database for each iteration.

Loops manages all actions required to adjust an optic and execute the steps. First, the loop requests the appropriate mediation component (MC) object to set up the laser and sensor configuration for a reference image. After the MC object executes the process to direct the shared resources to complete the configuration, the image is acquired and analyzed. This process is then repeated for the beam image. The positional difference between the reference and beam locations is corrected by adjusting the optics. The loop is repeated until the alignment difference is within the specified tolerance, or the maximum retry limit is reached and an operator is notified for manual mitigation [6].

## *Loop Examples*

For NIF laser alignments, the loops are classified into two types, “centering” and “pointing” based on the image plane in which the control images are collected Fig. 5.

**Centering loops** are used to position the beam within a relay plane in the optical system where the original beam formatting mask comes to focus after a relay telescope, typically referred to as the “Near Field.” Centering loop operations are required when the beam must be positioned precisely within the optical clear aperture to prevent beam clipping.

**Pointing Loops** are used to correct the propagating angle of the laser beam relative to the desired optical axis using images acquired while imaging in the back-focal plane of the relay telescope. This is the “infinite conjugate” and is typically referred to as the “Far Field.” Pointing loop

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operations are required when angular errors induced by ambient thermal variations, vibrations, upstream alignment corrections, and other factors exceed requirements without intervention.

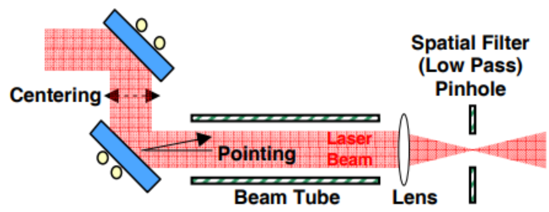


Figure 5: General schematic of pointing and centering.

## *Image Processing*

### *Algorithm Attributes*

All NIF control loops are designed to meet one or more specific accuracy requirements. The suite of 111 custom image processing algorithms that have been developed to meet these requirements are complex, varied, and wide-ranging, However, all alignment algorithms are required to contain four desirable attributes [7, 8]. First is computational efficiency. This is driven by the necessity that the full alignment of the laser chain is subject to a strictly timed alignment or shot cycle. Second, positional alignment accuracy is vital and, depending on the loop, can vary from sub-pixel to a few pixels to tens of pixels. A third attribute is adaptability. Changes and aging of hardware systems and the thousands of components within them require smart algorithms that can adapt to a variety of changing conditions. The fourth attribute is confidence in the alignment position estimates. Each image-analysis algorithm provides reliable uncertainty metrics [9] to indicate the successful processing of any given image.

### *Challenges*

The challenges of real-time image analysis include processing images with various types of noise, distortion, obscuration, and imaging artifacts. Noise sources include camera noise, diffraction noise, noise from stray light sources, gradient illumination, etc. Images also commonly experience distortion from defocusing, artifacts, and wavefront effects. In some loops, obscurants, clipping, saturation, or low pixel-to-feature images present unique processing challenges. Real-time image-analysis requirements for control loop processing demands attention to algorithm design efficiency. Figure 6 illustrates some of the variety of alignment images with examples of fiducials, characteristic shapes, intersecting reticles, pinholes, or the beam itself [10-14].

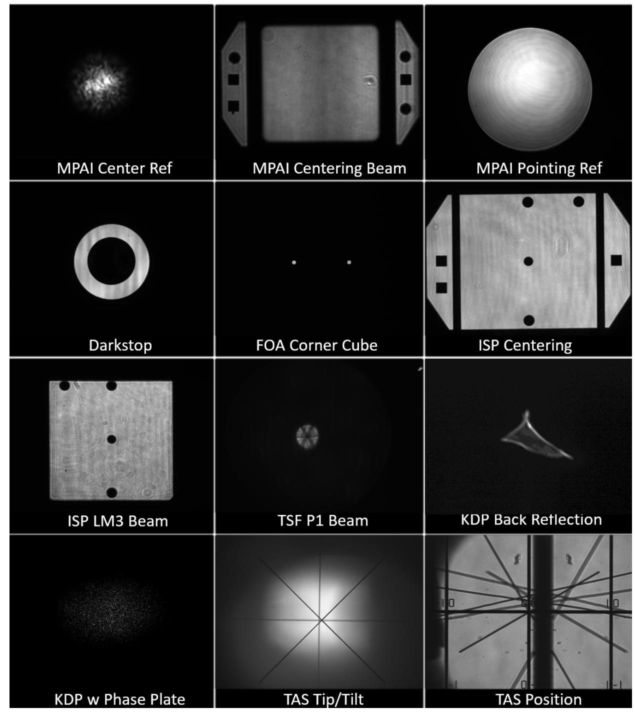


Figure 6: Sample of various images and fiducials including lines, circles, spots, squares, etc.

### *Off-Normal Processing*

For machine safety, image processing must guard against aligning the lasers with an improper or false image. As a first step, all images undergo a process to quickly identify unacceptable or 'off-normal' images [15, 16]. The off-normal processor is an initial image analysis step that contains a suite of selectable tests each of which analyzes the image and classifies it as a good or bad image. The tests look for basic or obvious image errors such as an image that is very dim or blank, missing the beam, all-white, etc. In addition, the off-normal processor has the capability to exploit prior knowledge from images that contain one or more fiducials or features. The processing can then perform pre-checks for expected location and sizing of expected features in the image [17].

### *Main Laser Image Analysis*

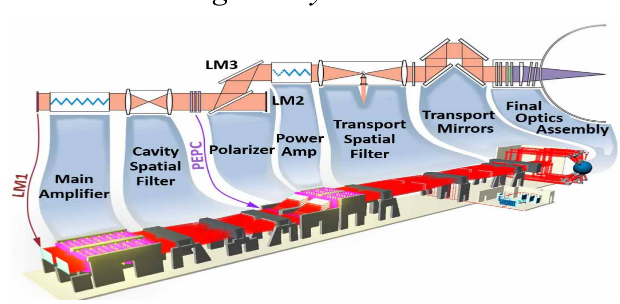


Figure 7: Main laser schematic of a single laser beam.

Implementing the capability to perform fast ignition experiments, as well as discovery science experiments places stringent requirements on the control of each of the beam's wavefront quality and pointing and centering accuracy as each beam (Fig. 7) travels to the target in the main laser bay. Prior to each laser firing, all 192 NIF beams are illuminated, resulting in camera images from up to 20 separate locations per beam. The images are processed using a suite of beam wavefront and centroiding image analysis algorithms. During this process, beam directions are iteratively and automatically adjusted using loop controls that provide high-precision beam positions at shot time. Interested readers will find details of many of these algorithms in [18-24].

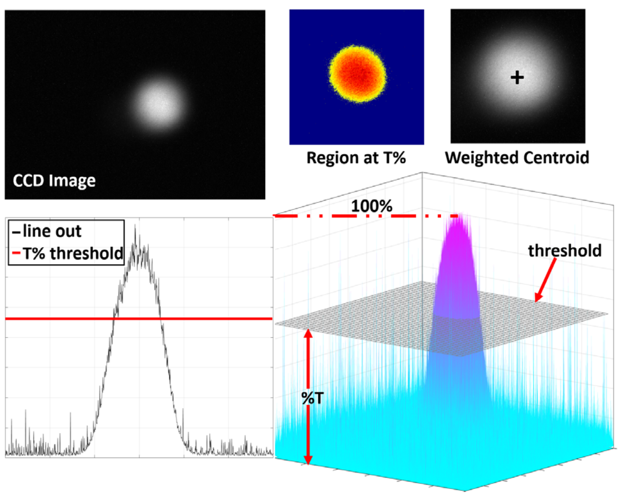


Figure 8: Standard AA image processing centroiding algorithm identifies largest connected region at a pre-determined intensity level and returns the weighted or geometric centroid of the region.

The main laser path shown in Fig. 7, most often employs a standard centroiding algorithm that is used throughout NIF and its sub-systems such as the advanced radiographic capability (ARC) [7]. After off-normal checks, the algorithm calculates a geometric or weighted centroid of the beam by identifying the largest connected region in the image at a given threshold intensity level shown in Fig. 8. The threshold consists of a percentage of the maximum image intensity added to the mean intensity. Alignment loops that are run using data-base driven control architecture can execute with location-specific parameters. Each loop can execute with tailored characteristics such as specific illumination conditions. As a result, every beam for the same alignment loop can potentially have different thresholds depending on system noise including hot pixels and neutron noise.

## *Target Area Image Analysis*

The NIF Target Alignment Sensor (TAS) provides a chamber center reference system (CCRS) architecture to align all 192 beams to target in the target chamber. TAS consists of a frame with four optical camera views of target chamber center (TCC) from the top, bottom, and two sides. Detailed descriptions and operation of TAS can be found in [25, 26].

The TAS is aligned to the target chamber using two orthogonally oriented auto-collimating telescopes referred to as the Chamber Coordinate Reference System (CCRS) arranged outside the target chamber as shown in Fig. 9. Details of TAS can be seen in Fig. 10. Once aligned to CCRS, the TAS is used to view the target which is, in turn, aligned to the imaging system. Image processing includes angular alignment (pitch and roll) and positioning (x, y, z).

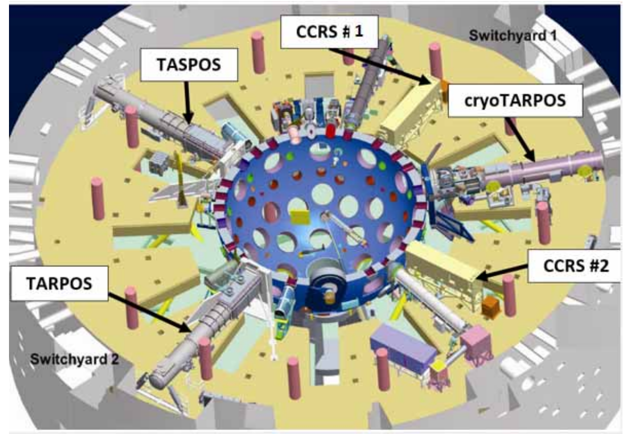


Figure 9: NIF target chamber cut-away showing target positioners and TAS CCRS cameras relative locations.

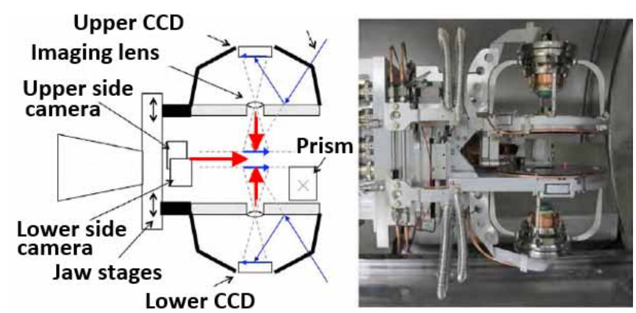


Figure 10: Diagram and photo of the TAS assembly, showing 3 directions for viewing the target (red arrows) and mirrors for equivalent plane beam alignment.

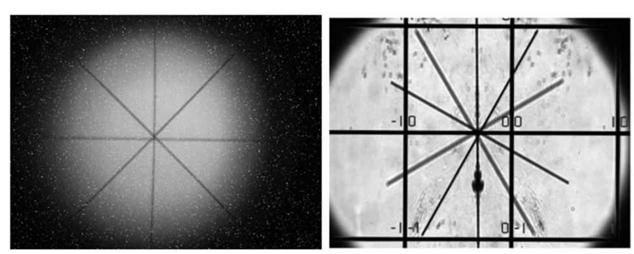

Figure 11: Example images for TAS pitch/roll (left) and centering (right) to the CCRS auto-collimating telescopes.

The crosshairs algorithm is used for both target alignments (Fig. 11). Crosshairs locates lines in the image at specific, expected angles [7]. Crosshairs is tolerant to noise, rotational variations, and is computationally inexpensive compared to other methods. After off-normal checks, each line of interest is rotated and segmented into periodic bands. The bands are compressed and resulting intensity projections are processed to locate the center of the edges of the line in each band. The set of centers are culled to remove outliers and a final set of points are fit to a line using either a modified Hough transform, or a simple regression fit. Intersections of pairs of lines provide the location of the reference grid relative to the beam center for final adjustment of the tip, tilt and centering of the target.

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### *Data Analysis*

The database-driven control architecture supporting the AA system provides the capability to fine-tune control-loop parameters specific to each of the 192 NIF beamlines as well as positioners such as the TAS. The value of key control-parameters in use during an alignment are archived, allowing post-shot review and trend analysis. Images, centroids, signal levels, uncertainty estimates, total loop iterations, and final actuator positions are a minute number of the total suite of archived parameters. Archived parameters are reviewed and analyzed to monitor the health of a variety of supporting subsystems.

The signal level of the images used in an alignment loop is an archived metric representing the health of the alignment light source used to illuminate the scene. Figure 12 shows 8-bit images of the back-lit Cavity Spatial Filter (CSF) pinholes illustrating marginal, nominal, and saturated signal levels. The images were archived for the same loop but different beamlines and are representative of the variation in signal levels across the system during alignment on a given shot. The illumination source in this case is a 1053nm laser that is injected into a fiber network and divided to support one cluster of 48 different beamlines. There are four light sources, each supporting one of the four NIF clusters. These lasers have a nominal lifetime and replacement schedule; however, the optical output can drop unexpectedly due to an internal failure mode resulting in marginal signal levels.

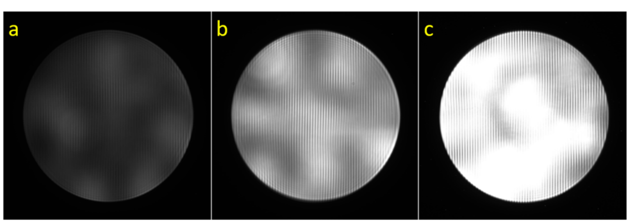


Figure 12: Back-lit CSF pinhole images used to confirm Main Laser Pointing: (a) marginal signal level, (b) nominal signal level, (c) saturated signal level.

Monitoring the signal levels is simplified by plotting the mean signal level parameter archived for this loop by location. The bar graphs in Fig. 13 illustrate the variation in illumination intensity for the backlit CSF pinhole by location. The relatively low intensity for all beams in Cluster 1 indicates the output power of the cluster-specific alignment light-source has dropped and requires maintenance. However, the NIF experiment schedule is demanding, and field service may not be possible until the facility configuration is appropriate. To facilitate alignment during the intervening shots until service is performed, the image acquisition parameters of camera exposure-time, camera gain, and camera-attenuator transmission are adjusted in the production database to increase the mean signal level to the nominal value. Moreover, for the nominally performing beamlines, their image acquisition parameters can be tuned to reduce or increase the mean signal level toward the optimum value.

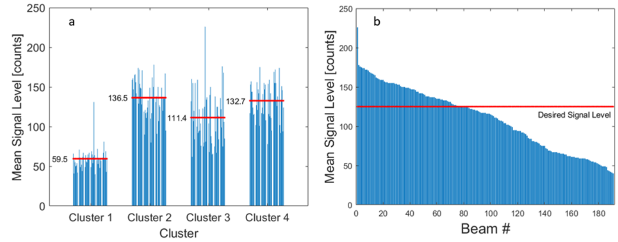


Figure 13: Mean signal level for the backlit CSF pinhole image by location for shot N230829-004 showing variation in illumination intensity: (a) mean signal by location, (b) mean signal level sorted by value, descending.

Maintaining consistent and optimum image saturation levels ensures consistent behavior by image processing algorithms and is enabled by monitoring the mean signal levels archived during the alignment process which is performed for every shot.

Analyzing critical data archived during AA operations helps to identify anomalies, improve planning, and evaluate overall performance critical to the NIF alignment system.

## OFFLINE TESTING

The complexity and interdependency of NIF AA requires careful checking of the ripple effects after any code change. Exercise and changes must be tested with the exact development environment as is used in production.

### *Testing Environment*

The testing is done in an environment where the entire scalable and easily adaptable NIF AA setup is created in emulation with the software devices which mimic the behavior of the actual devices in production for its processes and response time. Tests are performed frequently and in different scenarios in a safe, reliable, and effective manner.

### *Tool for Image Processing Testing*

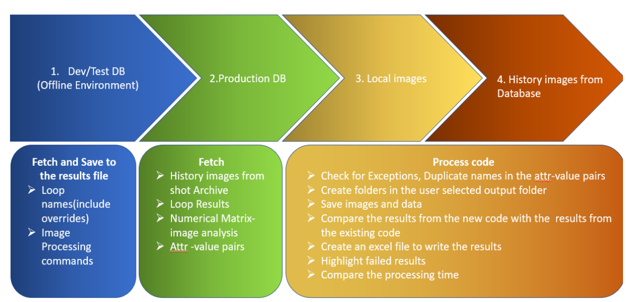


Figure 14: Flow of the IDL Code Analyzer testing tool process.

Image Processing code change is tested using a home developed tool, IDL Code Analyzer, where the code change is tested for all processes and functionalities that depend on the changed code. The IDL Code Analyzer identifies the code dependent code change using a pattern search, lists the loops and image processing commands, fetches the history images for the loops and image processing commands, runs the new code against the history

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images, goes through a compare standard evaluation procedure based on both new and history results quantitatively and determine the accuracies and associated errors. The results and images are saved in individual folders for detail analysis and the cumulative results are written down to an excel file in different individual spread sheets where the differences are highlighted for a quick review. The process for the testing is shown in Fig. 14.

### *Archiving Results of Testing*

Results and settings from the tests are archived in the database for analysis in case of failures and to improve working and performance.

## MAINTENANCE AND COMMISSIONING

Unstable or damaged optics, wear and tear of motors, settings affected due to system variation or optimization performed on any device which can lead to variations in results, are analyzed by Maintenance and commissioning toolset. Maintenance can be time-consuming and not accurate if done manually. Maintenance and Commissioning tools (MCT) are designed to run tasks in parallel for all 192 beamlines with minimum or no human interaction. They are also used in between experiments for different reasons, some device calibration, others to retrieve detailed operational data, making sure devices are in a set configuration to obtain high resolution images used for optic damage inspection. These tools have resulted in saving hours of operations time and helped in identifying the devices that require attention. Maintenance and commissioning toolset determines motor and device problems, as well as optimizing operational parameters due to system variation.

### *IOM Encoder Test Tool*

The motorized gimbal in the Integrated Optics Module (IOM) had occasional mechanical issues which are hard to triage and isolate. Significant operations time has been spent on malfunction identification. IOM encoder test tool runs beams in parallel and helps identify problems within minutes.

### *Camera and Attenuator Setpoint Tool*

The Challenges faced with a manual setup of the camera parameters which required significant of Operator's time, only one beamline could be processed at a time, adjustments were not done frequently, poor light level control created image processing uncertainty, necessitating too much operator manual intervention.

Camera and Attenuator Setpoint tool automates the settings for the camera parameters, so that images with optimal signal to noise ratio can be passed to AA for processing and process camera and attenuator parameters for multiple beamlines in parallel and completes in a minute or two.

## SUSTAINMENT PLAN

With the achievement of Ignition, NIF laid down the Future Sustainability and Modernization Plan which is aimed at a long-term plan to keep up with constantly evolving technology and maintaining NIF to the current standards in this faster changing world of technology. The goals of this plan are as follows:

- Finding the right and easy to use technology and tools that can be switched in the migration process if required, making sure of the availability of the resources, and offering flexibility.
- Balancing future development and modernization.
- Maintaining accuracy and execution.
- Create a test plan to constantly verify the functionality.
- Prioritizing and frequently comparing the performance with the history and significantly working on to improve the level of performance and efficiency.

## CONCLUSION

The fusion ignition results were repeated on Jul 30, 2023 [27]. The number of control loops needed for NIF alignment continues to increase due to refinement of alignment tasks and the addition of new hardware. As more experiments are being conducted in the NIF facility, the monitoring of system performance through logged performance metrics will be imperative. The automatic alignment system will continually be enhanced to improve accuracy, speed, robustness, and resource allocation[28].

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