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EXPERIENCES WITH LASER SURVEY INSTRUMENT BASED APPROACH TO NATIONAL IGNITION FACILITY DIAGNOSTIC ALIGNMENTS

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Abstract

The National Ignition Facility (NIF) uses powerful lasers to compress targets for the study of high energy density physics. Sophisticated diagnostics are placed close to the targets to record the results of each shot. The placement of these diagnostics relative to the target is critical to the mission, with alignment tolerances on the order of 500 microns. The integration of commercial laser tracker instruments into the NIF control system has improved diagnostic alignment in many ways. The Advanced Tracking Laser Alignment System (ATLAS) project incorporates commercial Faro laser tracker instruments into the diagnostic factory and the target chamber, providing flexibility and improved alignment accuracy. The system uses multiple retroreflectors mounted on each of the diagnostic assemblies. These are measured with the tracker and the location of the diagnostic hardware is interpreted as a 6 DoF (degrees of freedom) position in the NIF target chamber volume. This enables a closed loop alignment process to align each diagnostic such that the instrument line of sight intersects the aim point on the target. This paper provides an overview of how the laser tracker is used in diagnostic alignment and discusses challenges met by the control system developers to achieve this integration.

OVERVIEW

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) is the world's most energetic laser system for experimental research in Inertial Confinement Fusion (ICF) and high-energy-density (HED) physics. The NIF laser system consists of 192 laser beams which are focused inside a 10-meter Target Chamber (TC), delivering up to 1.8 MJ of ultraviolet light onto the mm to cm scale target.

The NIF has several Diagnostic Instrument Manipulators (DIMs) mounted to the target chamber, each of which can be used to place diagnostic instruments inside the target chamber for up-close viewing of the shot-time physics. Each DIM can extend up to 6 m, allowing the diagnostics to be positioned as close as 100 mm from the NIF target. Each DIM supports a variety diagnostics payloads, and based on the shot schedule, these payloads are frequently reconfigured. Each shot requires that the DIMs be precisely aligned to the NIF target.

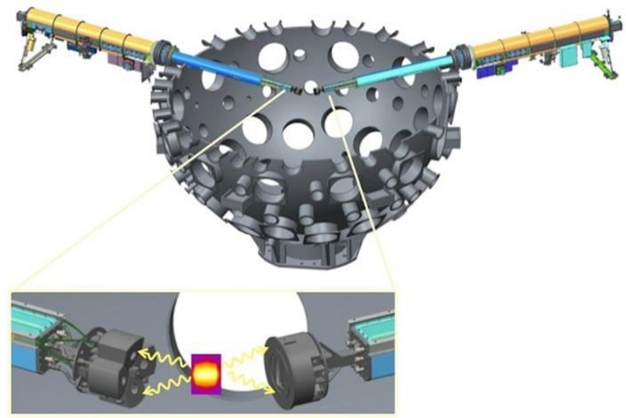

Figure 1: Two NIF Diagnostic Instrument Manipulators.

THE NEED FOR IMPROVED ALIGNMENT TOOLS

Prior to the introduction of the Advanced Tracking Laser Alignment System (ATLAS) system in NIF, all diagnostic alignments were performed using custom systems consisting of digital cameras, complex optics and lighting, and human interpretation of images as feedback for the alignment. Due to the narrow field of view of the optical systems, a dedicated optical system was required per diagnostic location [1,2]. NIF originally had three DIMs, and in conjunction with the ATLAS project there was a plan to add two more. The optical alignment system model would have led to five dedicated systems to maintain, and additional, sequential, manual alignments.

The many camera systems have to be removed for each high neutron yield NIF shot, and then reinstalled afterwards. Each of these systems also requires a clear view through the center of the target chamber, which constrained the sequence for alignment of the NIF experiment. Improving the alignment process flexibility and speed translates into cost savings and more experiments within a given period [3]. The main goals of the ATLAS project were:

- Have a single device to support alignment of multiple diagnostics
- Be easy to remove, re-install and recalibrate
- Not require visual interpretation of images for the alignment process

After an extensive evaluation and feasibility study of three different technologies and review of multiple laser tracker make and models, the Faro laser tracker was selected to be basis for this new alignment system.

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THE FARO LASER TRACKER INSTRUMENT

The FARO *Vantage* and *Ion* laser trackers are general purpose, portable coordinate measuring machines used in many industries including aerospace, shipbuilding, and forensics (Fig. 1) [4]. A tracker can locate individual retroreflectors (Fig. 2) to within 29 µm in 3 dimensions, using two angle encoders and a highly accurate absolute distance meter. Using several retroreflectors on a rigid part, the 6 degrees-of-freedom (DoF) can be obtained. From a fixed location, a tracker can swivel around and be pointed to reflectors within a large working volume: 360 degrees in azimuth, +77.9, -52.1 degrees in zenith, and up to 60 m distant [5].

Figure 1: FARO Vantage Laser Tracker (416 mm tall).

The NIF control system uses the laser tracker's Application Programming Interface (API) over ethernet communications. Core elements of the API are the three methods: Point (X, Y, Z mm), Spiral Search, and Measure Reflector (returning X, Y and Z mm).

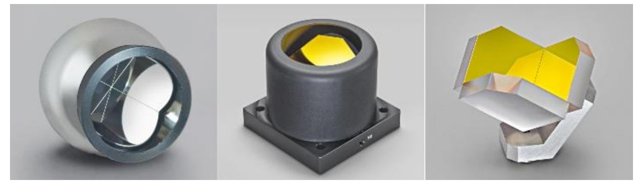
Figure 2: Sample retroreflectors (approximately 15-50 mm diameter).

NIF APPLICATION OF THE LASER TRACKER

The NIF ATLAS software operates three trackers to support diagnostic alignment: two located in the diagnostic *factory* and one located at a port on the NIF *target chamber*.

Diagnostic Factory Tracker Usage

The factory trackers are used to characterize the relationship between an instrument line of sight and the retroreflectors that are mounted to the outside of the instrument (Fig. 3). The assembly being characterized must be very rigid, so that these relationships will be maintained after transport and installation into the DIM and insertion into the NIF target chamber. This characterization of the instrument may be done days ahead of the shot when it is fielded.

To relate the diagnostic line-of-sight to the ATLAS retroreflectors, an alignment telescope is used to optically identify the imaging feature, such as a pinhole array. The telescope on the measurement station has multiple retroreflectors attached that have been characterized relative to the optical axis of the telescope. The laser tracker is used to measure the retros on the telescope and on the diagnostic. A technician identifies the diagnostic imaging feature in the telescope view. This procedure is repeated for as many instruments will be used for a given NIF shot.

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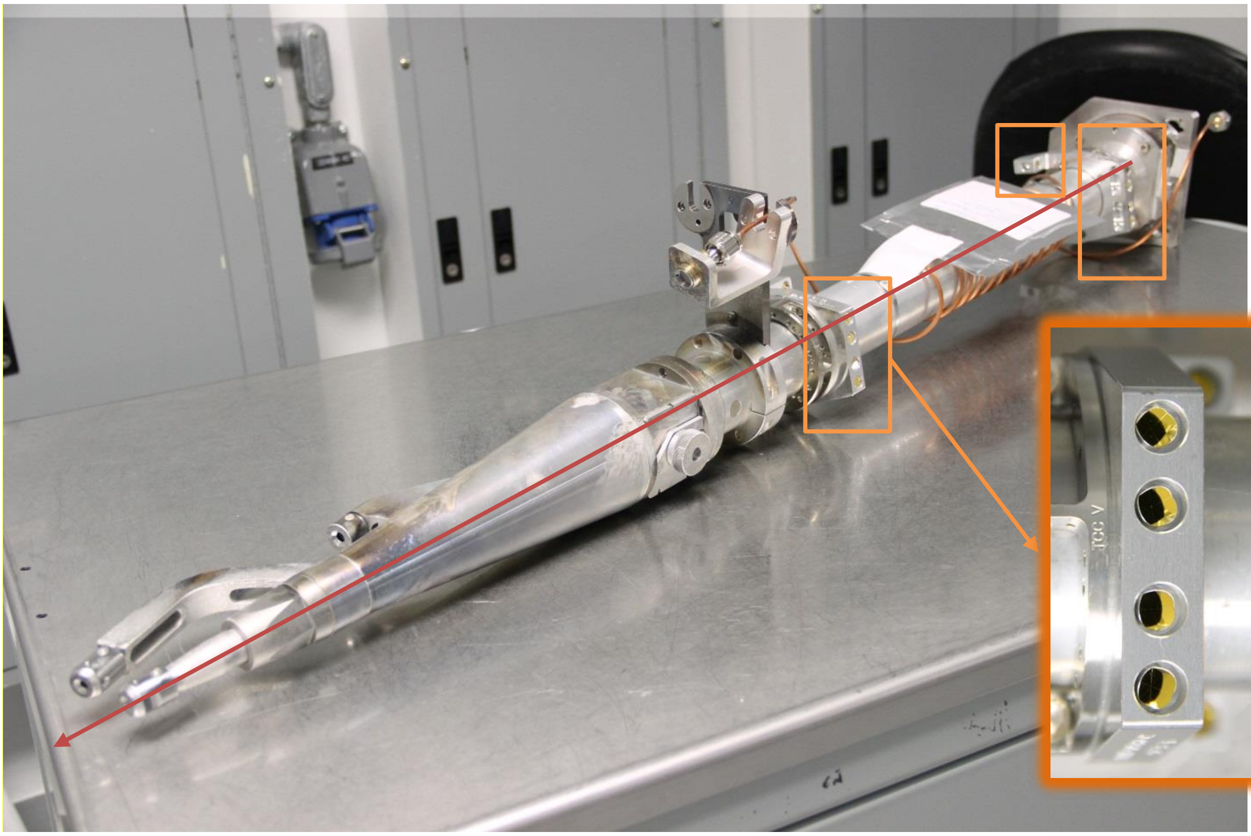

Figure 3: Diagnostic Snout with 12 ATLAS reflectors (orange boxes) and superimposed line of sight (red arrow). This diagnostic snout is approximately 1.2m in length. Four of the gold-coated retroreflectors are visible in the inset.

Target Chamber Tracker Usage

Once the instruments have been installed on the DIMs and inserted into the NIF target chamber (Fig. 4), the NIF control system uses the 3rd tracker to align those diagnostics. The wide field of view allows the single tracker to be used to locate the target and then align each of the DIMs in turn.

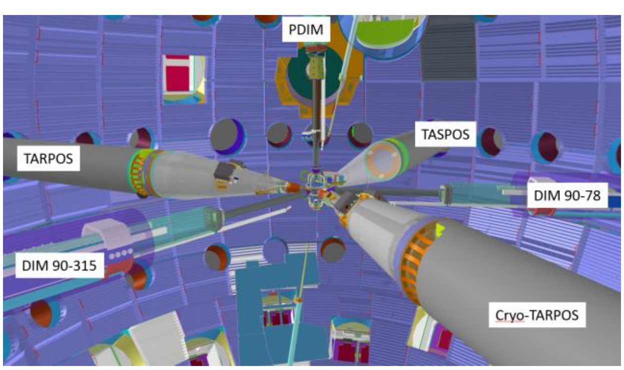

Figure 4: Laser Tracker's wide field of view.

The software first loads the characterization data from the factory and calculates the instrument line of sight relative to the instrument frame that is represented by the collection of retroreflectors. It then calculates the aim points for the instrument line of sight based on the shot goals.

ATLAS makes an initial 6 DoF measurement using reflectors on the Target Alignment Sensor (TAS), identifying the coordinate origin for the alignment of each of the diagnostics.

Then ATLAS follows a simple alignment algorithm for each diagnostic in turn:

Alignment Procedure

1. Measure the reflectors on the instrument
2. Compute the actual line of sight in 6 DoF (3D position and 3D orientation).
3. Compute the projected aim point (from line of sight and distance from target)
4. Compare with the desired alignment goal (often the center of the target).
5. If the difference is less than the alignment tolerances, stop.
6. Otherwise provide feedback to adjust the position using the DIM (commanding X, Y and Z moves).
7. Repeat (usually only takes one or two iterations).

ATLAS Measurement Durations

ATLAS measurement time per shot has a fixed component and a per diagnostic component. The fixed duration is approximately 1 minute to measure the target location and 2 minutes to measure the vacuum window position. The per diagnostic duration is 1 minute per iteration, with 2 or 3

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iterations being typical. For example, diagnostic alignment for a shot requiring diagnostics would take about 11 minutes of ATLAS measurement time.

SPECIAL CHALLENGES INTEGRATING THE LASER TRACKER

Finding Reflectors

Robust automation of a laser tracker depends upon being able to predict the coordinate of each reflector on the diagnostic, where the diagnostic hardware differs shot to shot. To lock the tracker onto an individual reflector, the tracker is pointed to an estimated location of the given reflector. The tracker is commanded to spiral until a reflector is found. The tracker expects a “Point” command, which needs to be within about 7 mm of the actual reflector location (because of our reflector spacing). Once it’s pointed, it will do a spiral search to find the reflector, then return the actual reflector location with full precision.

In the diagnostic factory, design values from the 3D CAD model of the instrument are used as approximate X, Y and Z locations for each reflector.

Kinematic Model

In the target chamber, finding reflectors is much more complex. The diagnostics are mounted on general purpose Target Area Positioners, which have complex motor controls and geometries of their own. The NIF control system had to be enhanced to use a kinematic model for these devices (Fig. 5). This allows the system to read the current position of the individual motors, and use trigonometry to calculate the approximate location of the diagnostic assembly carried by these positioners. Each motorized portion of the DIM has an associated 6DoF kinematic frame of reference, which is updated after each motor move.

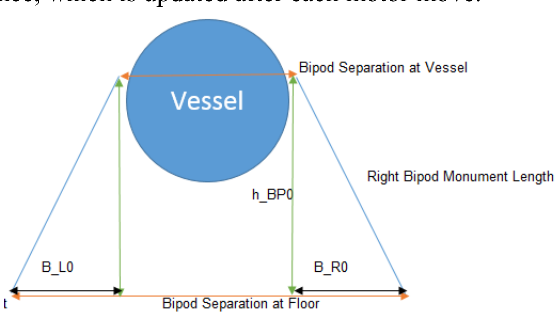

Figure 5: One component of the DIM kinematic model.

Frame Tree

The NIF control system has many frames of reference. Prior alignment systems were one-to-one with diagnostics being aligned, which simplified the frame relationships. Having one instrument (the tracker) to align all the diagnostics reduces frame-to-frame chain lengths, but it means that one device must be conversant with the frames of reference of all the diagnostics.

To provide a generalized solution, the NIF control system implemented a frame tree, which models all the 6 DoF relationships between each of the Target Area Positioners, their instruments, and the laser tracker (Fig. 6). The kinematic model was incorporated into the frame tree as well (the purple frames in Fig 6.).

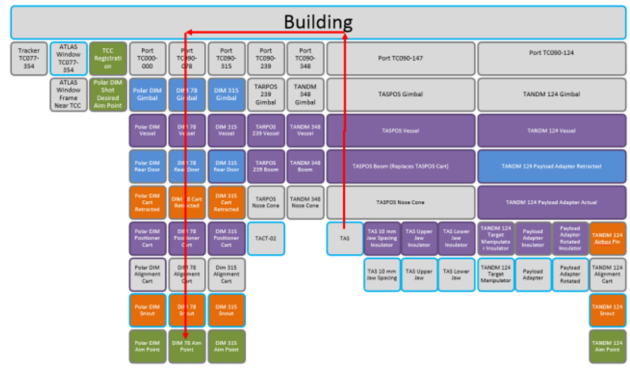

Figure 6: Portion of ATLAS Frame Tree.

Additionally, payloads on DIMs are changed frequently, and each payload has a unique physical geometry. Each time a new payload is installed, data gathered from the Diagnostic Factory is automatically loaded into the Frame Tree (the orange frames in Fig. 6). Some frames are defined by the alignment script itself, using shot-time data (the green frames in Fig. 6).

Each node in the frame tree is a 6 DoF transform to its parent. The ATLAS is implemented using Tait-Bryan x-y’-z” intrinsic rotational terms to specify the transforms, in part for ease of visualization. These can be converted to 4x4 transformation matrices, which when chained together can give the transformation between arbitrary nodes in the frame tree.

With this frame tree structure, the control system can easily ask questions such as “where is the diagnostic ABC aim point in the target frame of reference?” or “where is the DIM snout relative to the laser tracker?”

Looking Through a Window

The laser tracker is installed outside the target chamber, looking in through a vacuum window (Fig. 7). This is because the tracker can’t operate in a vacuum, and because it needs to be removed before high neutron yield shots (the neutrons would damage the tracker’s electronics).

Viewing through a window adds complexity to the operation of the tracker due to refraction of the tracker beams passing through the window. The vendor software only supports free-space measurement. Consequently, for the NIF, a refraction compensation algorithm has been developed to wrap around the measure and point commands sent to the tracker through the API. Measurements are post compensated to correct to the actual coordinate and point estimates are pre-compensated to provide the value in refracted space. The raw effect of refraction with the ATLAS window is to shift the perceived measurement distance on the order of 30 mm, and position by an amount that varies with angle relative to target chamber center. This compensation is a critical element of the ATLAS system since the required accuracy is to measure each reflector to better than 30 μm.

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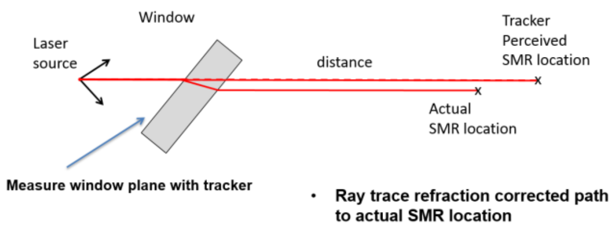

Figure 7: ATLAS Refraction Effect.

The ATLAS window was designed to have a very high optical quality to reduce uncertainty on measurements that could be caused by local variation or imperfections of the window. The material was selected to reduce index inhomogeneity and inclusions which would affect the beam quality in a manner that would be difficult to predict. Additionally, the surface polish is required to be very flat and smooth, which reduces beam deviation from local waviness.

The ATLAS system must be able to correct for refraction due to the window for reflectors measured at any point within the ATLAS field of view. As the tracker points to different locations, the incident angle on the window changes. To accurately compensate for any point, the algorithm dynamically calculates the effect of refraction.

The vacuum pressure differential on the window causes it to bow inward and change shape. Variation in pressure also cause the window to move around on the O-ring that the window floats against. To account for the bowing, the window is modelled as a simply supported pressure loaded disk and the theoretically deformed shape is assumed. The plane of the window is located prior to alignment activities by measuring 10 reflectors that are affixed to the outer surface of the window.

In order for the laser tracker to provide reliable measurements through a window, there must be an anti-reflective (AR) coating for the wavelengths of the tracker, in the case of ATLAS, the AR coating is designed for 632-660 nm and 1550 nm wavelengths. Without the coating, when measuring at near normal incidence the laser tracker receives a reflection from the glass that results in the distance measurement providing quasi-random results.

Angle from tracker to reflector

Because the tracker is in a fixed location, but the reflectors it is measuring are at many locations in the target chamber, the laser emitting from the tracker goes through the window at many different angles. This initial entry angle changes the effect of the refraction and needs to be included in the correction.

Surface angle of incidence

The outside of the window is at air, and the inside is at vacuum. As a result, the surface of the window has different refractive indices on each side.

Reflection

Despite having an anti-reflective coating on the window, there is still some reflection present when looking at reflectors very close to the NIF target chamber center at near-normal incidence to the window. In most scenarios, this doesn't impact NIF alignments, because there are no reflectors there (the NIF target is there), but work is still being done in the control system to characterize and minimize this effect.

Maturity of the Tracker API

Most other users of the Faro laser trackers control the tracker via a laptop and a dedicated ethernet connection between the two. The NIF control system, on the other hand, integrates many hundreds of various types of "smart" devices, all of which live on a network managed by network switches.

When first starting development on the NIF interface to the tracker, we quickly found that the tracker API doesn't work on a modern network or a subnet. The tracker needs to be connected to a dedicated ethernet port on a PC, with its API and client software running on the same PC. The NIF control system was adapted to interface to the tracker through this intermediate PC, removing this limitation.

Network Security

The original Ion tracker units purchased came with wireless networking support for the on-board digital camera. This interface needed to be disabled to comply with NIF computer security requirements, but no software mechanism was provided to turn it off. Eventually the equipment needed to be modified to physically remove these components from the tracker.

The newer Vantage model trackers do not have this shortfall.

INTEGRATION

The ATLAS system is implemented in several software layers (Fig. 8). At the lowest level, the FARO API communicates with the laser tracker, sending individual reflector commands: point, search and measure, in mm in the tracker's frame of reference.

Above that, the ATLAS device layer provides a 6 DoF interface, with a principle method "Locate Object". This layer converts between the 3D positions of individual reflectors, and the 6DoF position of the DIM payloads. This layer also manages the refraction correction, so the rest of the software doesn't have to know about the window effect.

The next layer up is the ATLAS Manager, which contains over 100 reference frame definitions, in a tree structure. Using the frame tree, higher level software can ask "tell me the position of the payload for DIM X relative to where the target will be aligned, from the perspective of the DIM." This layer also contains the kinematic model. The kinematic model maintains dynamic frames in the frame tree, describing the location of the DIMs to the chamber. Each time a DIM motor moves, several kinematic frames are updated to model the current location of the DIMs.

On the positioner side, the lowest level of control is the command of individual motor devices. These allow basic insert/retract commands.

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Above that are the DIM devices. These know how to perform multi-motor moves, with configurable cross-coupling. This software manages the motor moves so that motors start and stop at the same time, giving an overall linear behavior to the moves.

At the highest level for the DIM, the DIM Manager takes move requests in the DIM frame of reference, and uses the cross-coupled layer to perform the action.

Tying the ATLAS measurements and DIM movements together is the ATLAS DIM Alignment Target Area Alignment Tool (TAAT) script [6]. This layer knows about the alignment sequence, goals and tolerances. It alternates between requesting payload position from the ATLAS manager and commanding payload moves to the DIM Manager.

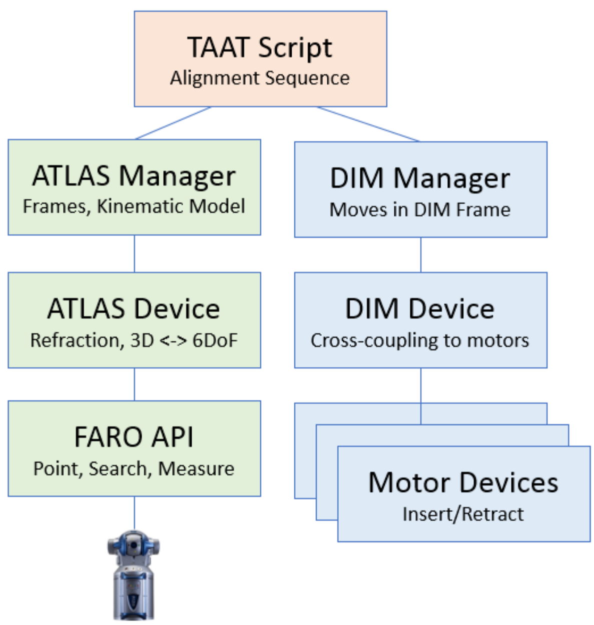

Figure 8: ATLAS Software Layers.

AUTOMATION

All prior NIF diagnostic alignment systems involved a person looking at a camera image of the diagnostic, as part of the alignment loop. This prevented closed-loop automated alignments.

The ATLAS system still requires a human to do a similar visual interpretation at discrete steps in the process. The first has been moved back to the diagnostic factory, days ahead of the actual shot. This is where the relationship between diagnostic line of sight and reflectors is established. This allows automated, closed-loop alignment of the diagnostic for shot in the NIF target chamber. The second is for final verification that the instrument is positioned in a safe location for the shot. This both saves time and reduces chances of human error during the alignment.

MONITORING SYSTEM OPERATION

All of the laser tracker operations are automated, and in the course of a NIF shot there may be hundreds of individual reflector measurements made, and dozens of frames are updated in the frame tree. Tracking the performance of these activities is an important operational metric. If there are any system failures, the history of activity is a critical diagnostic for technical support.

To present this large data set in an easy-to-understand format, NIF uses custom Splunk dashboards to extract and visualize performance data for the ATLAS system [7]. Figure 9 shows a sample from Splunk identifying outliers in the kinematic model for one of the DIMs.

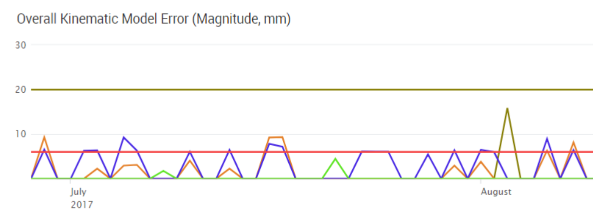

Figure 9: Example Splunk dashboard panel.

TESTABILITY OF THE INTEGRATED SYSTEM

One of the great strengths of the ATLAS system is its testability. This is especially important in this phase of the NIF program, where shots are occurring 5 days a week, 24 hours a day. The two remaining days are for maintenance and commissioning, and it's costly using that time to troubleshoot new software systems.

Optical alignment systems require complex optics and lighting systems, which were impossible to replicate outside of the NIF target chamber. By contrast, the laser tracker doesn't have any lighting requirements, and sees all reflectors equally well.

This has allowed the use of an offline simulator to test all layers of the alignment software. The simulator has a laser tracker, a window (air on both sides), and small-scale Target Area Positioners. Full alignment sequences can be performed there prior to software delivery to the NIF system itself.

This simulator supports both new feature testing as well as regression testing – making sure other changes to the control system do not impact the laser tracker behaviour.

MANAGING THE ERROR BUDGET

Any alignment system has to meet the alignment tolerances in order for the diagnostic to capture data of the subject event. Many of the diagnostics at NIF have a requirement to be aligned within 500 µm in X and Y (pointing) and 2 mm in Z (distance) to the aim point on the target. In order to meet that overall requirement, error analysis was performed, identifying error contributions for each portion of the system, starting at the diagnostic factory and ending with the ATLAS alignment in the target chamber (Fig. 10). This analysis varies by instrument, measurement, distance from target, retroreflector spacing and many other variables. This in turn guides the diagnostic designers in the design for retroreflector placement on the instruments.

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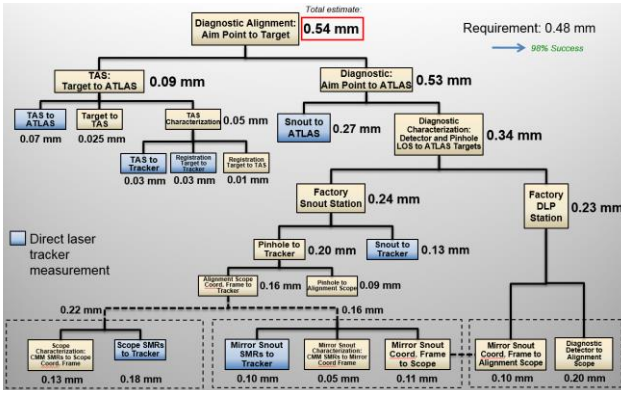

Figure 10: Sample ATLAS Error Budget.

RESULTING PERFORMANCE

ATLAS has exceeded its goals for alignment performance and is improving shot-to-shot durations. Images captured by NIF diagnostics that were aligned with the ATLAS system, show pointing accuracy of 120 µm RMS relative to the NIF target. This meets the 500 µm requirement for these diagnostics with plenty of margin. One specialty diagnostic which requires even tighter alignment tolerances is also being successfully aligned with ATLAS. Ongoing optimization in the alignment sequence continues to reduce alignment durations while retaining the same accuracy.

CONCLUSION

The addition of the laser trackers to the NIF diagnostic alignment systems has been a great success. The system has provided better alignment accuracy than prior systems for standard x-ray imaging, and allows automate feedback for diagnostic alignment. The single laser tracker at the target chamber can be used to align multiple diagnostics fielded a shot (instead of one per alignment system). The laser tracker is easy to remove and reinstall, preventing damage when high yield shots occur. As additional DIMs come online, this same laser tracker will be able to support the alignment with no additional hardware being required.

ACKNOWLEDGEMENT

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