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NEW VISUAL ALIGNMENT SEQUENCER TOOL IMPROVES EFFICIENCY OF SHOT OPERATIONS AT THE NATIONAL IGNITION FACILITY (NIF)

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Abstract

Established control systems for scientific experimental facilities offer several levels of user interfaces to match domain-specific needs and preferences of scientists, technicians and engineers. At the National Ignition Facility (NIF), the low-level device panels address technicians' need for comprehensive hardware control, while Shot Automation software allows NIF shot directors to advance thousands of devices at once through a carefully orchestrated shot sequence. MATLAB scripting with the NIF Layering Toolbox has enabled formation of intricate deuterium-tritium ice layers for fusion experiments. The latest addition to this family of user interfaces is the Target Area Alignment Tool (TAAT), which guides NIF operators through hundreds of measurement and motion steps necessary to precisely align targets and diagnostics for each experiment inside NIF's 10-meter Target Chamber. In this paper, we discuss how this new tool has integrated familiar spreadsheet calculations with intuitive visual aids and checklist-like scripting to allow NIF process engineers to automate and streamline alignment sequences, contributing toward NIF shot rate enhancement goals [1].

INTRODUCTION

The National Ignition Facility 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 the 10-meter Target Chamber (TC), delivering up to 1.8 MJ of ultraviolet light onto the target.

Eleven target and diagnostic positioners are used to precisely position NIF targets and diagnostic instruments inside the Target Chamber. NIF positioners are large electromechanical systems with several degrees of freedom. Positioners are 10-15 meters long and extend up to 5 meters reaching NIF's Target Chamber Center (TCC) (Fig. 1).

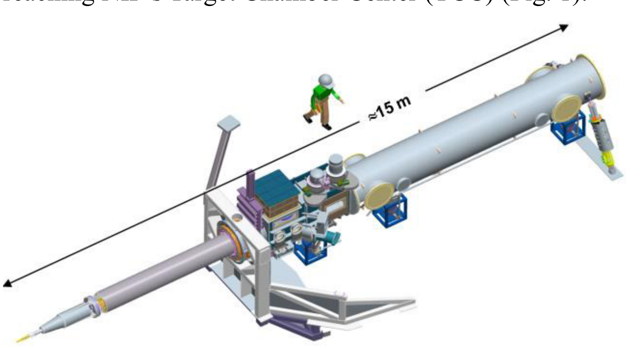

Figure 1: A NIF positioner.

NIF targets, diagnostics, and laser beams need to be precisely aligned for every NIF experiment (also called "shot") (Fig. 2). The alignment tolerances are determined by the type of diagnostic and the experimental requirements, and can be as demanding as tens of microns when aligning pinholes of the neutron imaging systems.

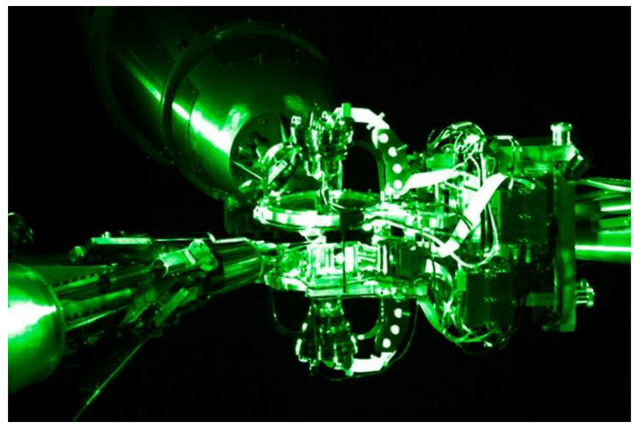

Figure 2: Multiple positioners at NIF TCC.

Most of the target and diagnostic alignments at NIF are performed by trained operators using visual features and alignment aids. Video cameras of various orientation and zoom levels support this process, such as the 50-megapixel Opposed Port Alignment System (OPAS).

With the addition of the Advanced Tracking Laser Alignment System (ATLAS), the exact positions of diagnostic instruments can be measured without relying on a human operator. This new NIF alignment capability opens the path toward precise, fully automated diagnostic alignment at NIF [2].

NEED FOR AN ALIGNMENT TOOL

Target and diagnostic alignment operations at NIF consist of hundreds of steps performed by skilled operators. Each experiment at NIF is unique due to variations in target designs and changing diagnostic configurations. The specifics of the experimental setup, target and diagnostics metrology all influence the alignment process. Based on these data, the expected positions of the alignment features are computed for each step. Once the equipment is coarsely aligned, the operator identifies the alignment features using one or more cameras and determines the feature location as projected on the camera image plane. NIF camera user interfaces (UI) are equipped with graphical alignment aids (GAA) which allow operators to draw lines, rectangular boxes, circles, etc. and then read out the positions of these aids. Using both the expected and actual positions of the

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alignment features, the operator can determine whether a correcting move is needed based on the alignment tolerance. To perform the move, the coordinates are input into the motion control software UI. The motion control system displays the proposed move as an overlay on the camera UI, prompting the operator to assess whether the move is adequate and compliant with the collision avoidance rules. Once the move is approved and executed, the operator repeats the visual identification and measurement steps described above.

Prior to the development of this software tool, the alignment subject matter experts (SME) were relying on spreadsheet software to document alignment procedures. The spreadsheets include fields where the operators manually enter the experimental setup, metrology and measurements data. These data entry fields trigger spreadsheet calculations developed by the SMEs. The calculations produced the coordinates of the required correction moves, if any are needed based on the alignment tolerance criteria.

By interviewing SMEs with many years of alignment checklist development experience, we learned that the spreadsheet software allowed them the required flexibility in adjusting the procedures, as well as ease of developing new checklists from the existing ones. Importantly, the embedded spreadsheet calculations enabled SMEs to "code" and "debug" all computations before the operator "runs" them during production alignments. In case of unexpected situations, the SMEs could do "forensics" by entering production data into their copy of the spreadsheet.

For our new software tool to be useful and accepted, we needed to bridge the domain gap into the space of alignment SMEs and operators and to match their concepts of operations and tooling.

CONTROL SYSTEM USER INTERFACES

It is common for control systems to develop several levels of user interfaces. The low-level control panels for individual devices provide full control over numerous settings and commands – usually mirroring the front panel of the corresponding instrument and allowing a technician to fully operate and troubleshoot the hardware remotely. Higher-level "supervisory" UIs coordinate operation of several devices and implement one of the standard control sequences, such as setup-arm-acquire-store. Interfaces to scripting languages such as Python or MATLAB allow scientists to design complex sequences of control actions intermixed with specialized data or image processing.

At NIF, the individual "maintenance" panels are addressing the need for comprehensive low-level control of a single device. On the opposite end, the Shot Director UI orchestrates the entire NIF, thousands of devices, into a tightly controlled, carefully optimized shot sequence, hiding all low-level details [3]. The NIF control system supports several scripting languages by providing library interfaces for MATLAB, JavaScript, Groovy, and BeanShell. The MATLAB Layering Toolbox was a key enabling factor for NIF successes in forming perfectly round and smooth layers of deuterium-tritium ice for thermonuclear ignition experiments [4].

GOALS AND CHALLENGES

The design and development of the Target Area Alignment Tool (TAAT) (Fig. 3) was undertaken to improve efficiency of alignment operations, a key enabling factor for the increased NIF shot rate [5]. The software requirements were derived from the multi-year critical path analysis and from the working group collaboration with NIF alignment operators and SMEs.

Automated Checklists

From the initial technical assessment, it became clear that NIF's target and diagnostic alignment processes cannot be fully automated to a "hands-off' level, at least for now. While NIF fully relies on automatic image analysis for laser beam alignment [6], visual identification and precise location of target alignment fiducials cannot be currently trusted to an image analysis algorithm due to variations in target designs, diagnostics configurations, lighting conditions and alignment sequences. A hybrid man-machine solution was needed.

Checklists have been utilized across NIF as a primary tool in achieving human operator efficiency while maintaining low error rate in 24x7 operational environments constrained by the cleanroom, hazardous materials and radiological protocols. Both traditional paper and electronic iPad checklists are in use at NIF [7].

By positioning TAAT as an automated checklist, we have immediately achieved good coherence with the established processes and we have gotten access to accurately documented use-case scenarios in the form of existing checklists. By analyzing these checklists, we have identified steps well suited for software automation.

There are "good" checklists and "bad" checklists [8]. By automating out repetitive copy-paste and mouse-click operations, we can convert "bad" checklists into "good" ones with few well-defined pause points, a focus on essential operations, and a trust of operator professionalism. The goal is to free operators' minds from the memory overload of mundane operations and instead focus humans on key operations which computers still fail to do.

Preserving SME's Ownership

Once the operators learn to rely on the checklists, it becomes crucially important that they remain correct and up-to-date. Trusting an outdated checklist is worse than not having a checklist at all.

With the development of the new TAAT software, we wanted to preserve full ownership of alignment SMEs over their checklists. Given that NIF alignment SMEs' backgrounds lie in mechanical, optical or facility operations fields, we cannot assume their software engineering proficiency is sufficient to code in traditional programming languages. On the other hand, the same SMEs have previously developed

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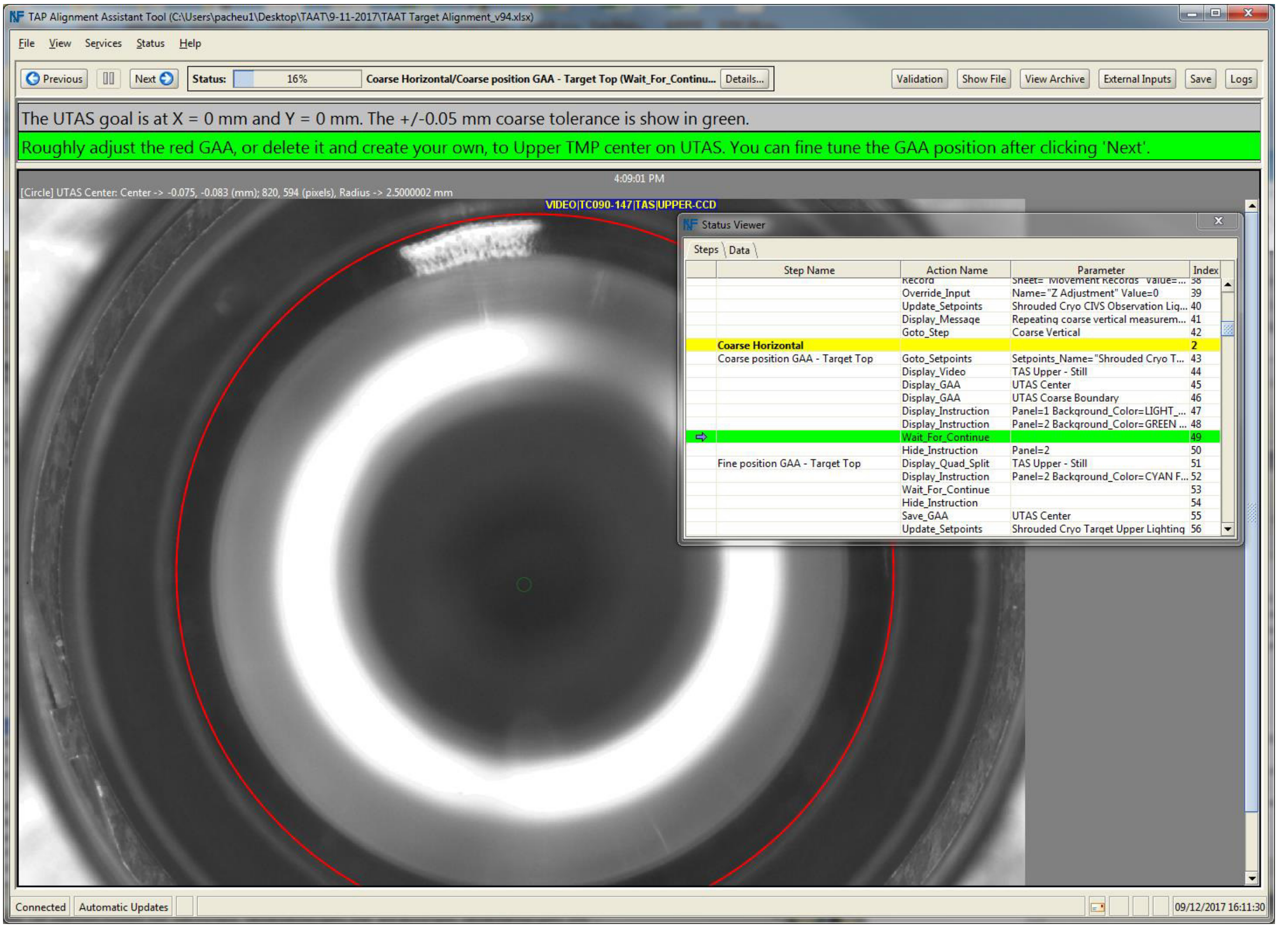

Figure 3: The Target Area Alignment Tool executing an alignment sequence.

and maintained highly sophisticated, data-driven branching checklists using spreadsheet applications.

From the user workgroup discussions, we realized that the best way to bridge the domain gap is to allow SMEs to “program” the automated checklist using traditional spreadsheet software.

Embedding Simple Spreadsheet-like Calculations

While reviewing pre-TAAT checklists, we observed that alignment SMEs already use spreadsheet formulas to “automate” data processing operations:

- Computing correcting moves
- Coordinate transformations
- Table lookups
- String concatenation and formatting
- Conditional completion indicators
- Conditional hiding of checklist sections

These calculations and data conversion operations vary between the alignment procedures and change frequently over time. It is highly desirable to keep these calculations in the spreadsheets, under SME control, to allow rapid enhancements and corrections and to prevent introduction of errors when translating into traditional programming language.

Solving Copy-paste Issues

One inefficient pattern was immediately obvious in the pre-TAAT spreadsheet-based alignment process: manual data entry and copy-pasting of data between software applications. While the spreadsheets are “programmed” by SMEs to perform the calculations, all data inputs and outputs were left for the operator to do. First, the experimental setup data must be copied from the NIF Campaign Management Tool (CMT) [9] and metrology information entered from the NIF Location Component State (LoCoS) [10] application. Then, for each alignment step the visual measurement coordinates are entered into the spreadsheet, with calculation results typed back into the motion control software UI.

Unlike spreadsheet software, the newly developed TAAT tool is an integrated component of the control system, which has direct access to the experimental setup and metrology data; it can submit requests directly to the motion control system. To capture operator placement of the alignment aids, the TAAT embedded a video interface panel to allow creation of the GAAs. For the new ATLAS laser tracker alignment system, the tool can interact with the measurement system directly.

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Specialized Task-centric Video UI

While reviewing operator-software interaction patterns, additional inefficiencies were recognized. When performing alignment operations, operators need to observe, identify and measure features on several video UI panels. The video streams are from different cameras and the sets of cameras vary for different procedures and even within the procedure step-to-step. The placement, size and order of UI windows is unpredictable in common operating systems due to the "stacking" of window managers. We observed that the experienced operators carefully aligned video camera panels side-by-side before proceeding with the alignment, which assures consistency, minimizes chance of error, but also takes time.

A more controlled side-by-side placement of the windows was desired, similar to tiling window managers [11]. Ideally, the placement and source of video panels should be defined by the SME in the alignment sequence spreadsheet; so for each phase of the process, the correct set of video streams is automatically presented to the operator.

For precise placement of the alignment aids, zoom-in and full-screen features were requested, with a simple restoration to the predefined tile layout.

Finally, a NIF target-specific use case was described: when aligning NIF hohlraums from the top or bottom view, the location of the Laser Entrance Hole (LEH) is determined by placement of 3-4 markers on the LEH border. To achieve maximum precision, a zoom-in is desired. However, the zoom-in also pushes other markers out of the field of view. Ideally, the TAAT video panels should be equipped with a specialized zoom tool which keeps the LEH border sections in view while leaving out the emptiness of the hole.

Logging All Data, Tracing Execution Steps

NIF alignment SMEs required recording all data and the execution timestamps from the alignment processes. In the event of an off-normal situation, the full set of data supports the root-cause analysis and helps to pinpoint the problem in the controls software, metrology data or an operator action. Collecting years' worth of data also allows long-term trend analysis. Detailed timings of the execution sequences are invaluable when looking for opportunities to tune up efficiency of the processes and systems [5].

TRADEOFFS AND SOLUTIONS

Integrating SMEs' Spreadsheets

From the alignment tool working group discussions, it became clear that spreadsheets represent the most familiar, well-understood format for describing alignment sequences. Ideally, the spreadsheet application would be equipped with a sequencer execution engine and a direct interface to the control system. The control system did not presently support this interface, and developing in this direction would be a significant diversion from the NIF control system architecture and the skillset of our software engineers. After additional consultations, we refined the spreadsheet interoperability requirements to the following:

- For authoring of the alignment sequences, the SMEs use spreadsheet software, including formulas for calculations and data manipulation.
- For execution of the alignment sequences, the operators do not need a spreadsheet application. Instead, it is desirable to hide the details from the operators and prevent them from editing the sequence.
- The execution of the alignment sequence should be performed by a control system application which will have same 'look and feel' as other control UIs.

Accepting these constraints has opened a path towards implementation of the new tool using the NIF controls Java platform, leveraging the existing frameworks to provide the necessary access to data and control interfaces.

For importing spreadsheets with alignment sequence definitions, we have chosen Apache POI library [12]. The library supports import and export of spreadsheet documents within a Java application. Importantly, the calculations of the spreadsheet formulas are also supported by the Apache POI, which means that the TAAT tool will perform computations as developed by the alignment SMEs.

During library evaluation, we discovered a shortcoming in the Apache POI calculation engine: the array and matrix functions were unimplemented. Since the library is open source software, we established a collaboration to remedy this deficiency, with a software patch offered back to the Apache POI project [13] to implement the missing functions.

We have agreed with alignment SMEs on the following "coding" conventions:

- Alignment sequence steps are represented by rows in the spreadsheet. Separate worksheets may be used to decompose the sequence into logical blocks.
- Queries and commands to the control system are invoked by the keywords in the sequence.
- Inputs and outputs are mapped to spreadsheet cells or cell ranges.

Sequencer Engine

Once the alignment sequence is imported from the spreadsheet file, it is ready to be executed by the TAAT sequencer engine. To maintain better structure, the sequence is divided into steps, with each step invoking several actions. Steps can be re-used in the sequence.

The execution of the sequence can be paused and stepped back and forth for troubleshooting. Conditional execution of the steps is supported to allow simple branching.

Most of the alignment sequence runs without operator involvement. Optionally, the operator can bring up TAAT's status panel to watch execution progress.

When user attention or action is required, an alignment sequence keyword causes TAAT to display operator instructions, pause for the decision, or wait for the manual visual feature measurement.

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Visual Interface

TAAT includes a video/image UI panel which addresses task-specific needs of this tool. The layout of the panel is defined by a keyword in the alignment sequence file, so the SMEs can direct that a specific set of cameras in consistent order is presented to the operator at the appropriate time. For example, for NIF target alignment, the operator places circular alignment aids on top and bottom views of the LEH, as well as markers on the side views (Fig. 4).

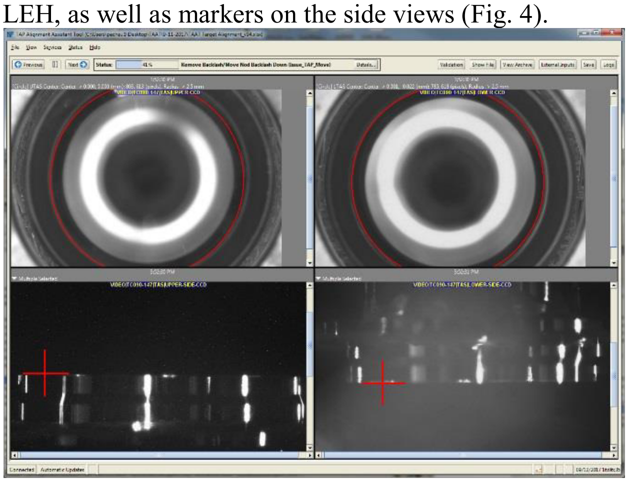

Figure 4: Alignment aids placed on four video panels.

To address the important use case of measuring the target LEH circle, TAAT provides a multi-segment zoom capability, where several panels are synchronously zoomed while maintaining their individual center positions (Fig. 5).

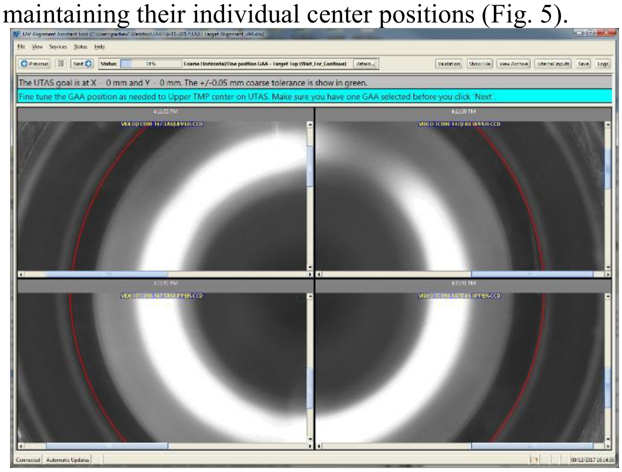

Figure 5: A multi-segment zoom.

Logging and Archive

Alignment SMEs have requested that for each alignment operation all inputs, outputs and intermediate calculation results be captured as they were presented to the operator at the time of execution. This requirement was satisfied by providing a “save workbook” keyword, which SMEs can insert at the appropriate place in the sequence. The data is saved in the spreadsheet format and automatically populated with relevant setup, measurement and calculation results using the alignment sequence file as a template.

CONCLUSION

With the introduction of TAAT into NIF alignment operations, the tool has helped to streamline alignment operations and contributed toward the NIF facility efficiency goals [5]. Compared with the previous manual alignment approach, the tool saves 30 minutes per alignment sequence on average, and it reduces or eliminates a consider-

Table 1: TAAT Savings of Alignment Actions

Metric	Manual	TAAT	Savings
Number of measurements	1413	763	46%
Number of moves	130	34	74%
Number of data entries	83	0	100%
Number of move choices	26	0	100%

Future savings are expected from integrating TAAT with the ATLAS laser tracker alignment system, which replaces operator visual measurements with precise, automated operations.

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