

AUTOMATED EXPERIMENTAL DATA ANALYSIS AT THE NATIONAL IGNITION FACILITY

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Abstract

The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory is a 192-beam 1.8 MJ ultraviolet laser system designed to support high-energy-density science, including demonstration of inertial confinement fusion ignition. After each target shot lasting ~20 ns, scientists require data acquisition, analysis and display within 30 minutes from more than 20 specialized high-speed diagnostic instruments. These diagnostics measure critical x-ray, optical and nuclear phenomena during target burn to quantify ignition results and compare to computational models. All diagnostic data (hundreds of Gbytes) are automatically transferred to an Oracle database that triggers the NIF Shot Data Analysis (SDA) Engine, which distributes the signal and image processing tasks to a Linux cluster. The SDA Engine integrates commercial workflow tools and messaging technologies into a scientific software architecture that is highly parallel, scalable, and flexible. Results are archived in the database for scientist approval and displayed using a web-based tool. The unique architecture and functionality of the SDA Engine will be presented along with an example.

NIF DATA REQUIREMENTS

The National Ignition Facility [1,2] is a stadium-sized building that houses the world's most energetic laser system. Its purpose is to allow scientists to study high-energy-density physics and, in particular, to investigate fusion ignition as a potentially limitless clean energy source and as the primary reaction that fuels the stars. The 192 laser beams of NIF are amplified and focused toward the center of a 10-meter diameter target chamber where various mm-sized targets receive up to 500 TW of laser power in a few nanoseconds. NIF is designed for a 30-year experimental lifetime, during which many thousands of pulsed-laser "shots" will occur and many peta-bytes of data will be acquired and processed.

Scientists working in NIF must be able to quickly analyze and interpret the data obtained from more than 20 specialized diagnostic instruments located at the NIF target chamber. While preparing for an experiment, the analyses help guide laser alignment, focus, and other tuning parameters necessary to accomplish experiment goals. After an experiment, the analyses help interpret the raw data collected from the diagnostic instruments. In combination, these analyses constitute the physical measurements on which all NIF experiments are based.

NIF Data Analysis Requirements

In this paper, we describe the Shot Data Analysis (SDA) system that processes the experimental data from NIF target shots. The SDA Engine is the first production-ready automated analysis system of its kind. Shot data is automatically captured and archived into a database, which triggers the model-driven architecture to launch analyses for each diagnostic. Commercial workflow tools and messaging technologies (queues) are employed in the design. SDA is currently supporting daily shots from NIF operations and producing analysis results for at least eight diagnostics, with more added each month.

The high-level requirements of SDA are that the data be

- Secure – stored in a safe data repository [3]
- Accurate – with error bounds and quality metrics
- Visible – to stakeholders, on the NIF web, in ~30 min.
- Available – to be downloaded at all processing steps
- "Pedigreed" – with a known history of algorithms, versions, calibration, configuration, raw data, etc.
- Reviewable – to be approved by responsible party.

To meet these requirements, the SDA software must be published and "transparent", with design reviews, revision control and results validation.

SHOT DATA ANALYSIS ENGINE

The Shot Data Analysis Engine was first deployed on NIF in 2008. The highly flexible and scalable analysis framework (Figure 1) features a parallel architecture that provides:

- automatic triggering of analysis upon new data arrival;
- analysis workflow sequencing;
- data provisioning from various data sources;
- data mapping to analysis functions written in Interactive Data Language (IDL®) [4]; and
- archiving of results with their "pedigree" (a record of the data inputs and analysis software version).

The framework's scalable, parallel architecture is accomplished through the use of two key technologies: (1) message queues with Java messaging that dynamically schedule and balance analysis tasks across all available resources—*i.e.*, processes and processors—and (2) a commercial, industry-standard workflow processor called Business Process Execution Language (BPEL) that orchestrates the analysis and integrates external data repositories through Web Services.

Shot Data Analysis is defined in two parts: (1) the Analysis Framework, which supervises the analysis process by controlling scheduling, data flow, and data services, and (2) the Analysis Modules, which are the software tasks that perform data processing functions.

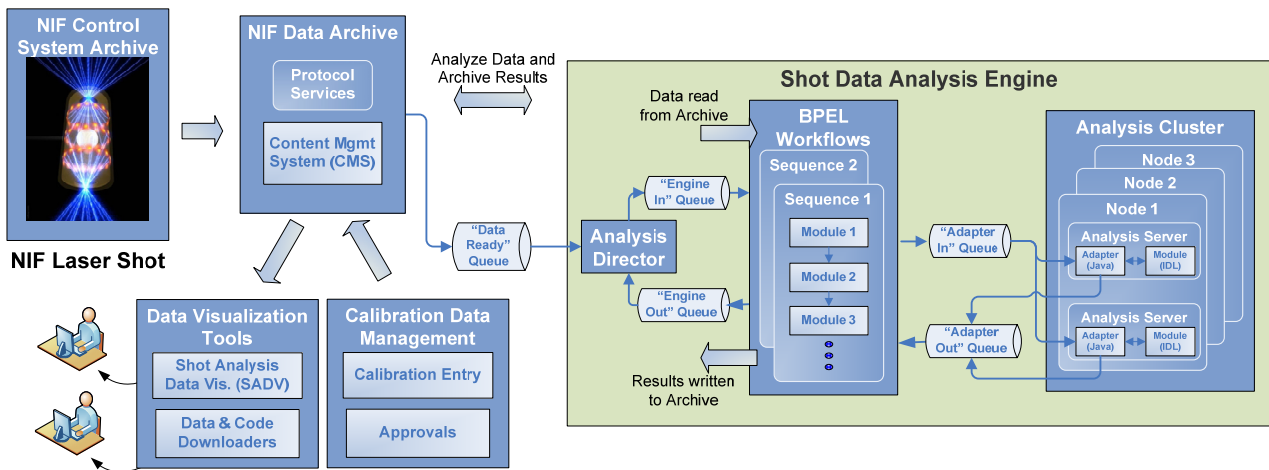


Figure 1: NIF shot-data analysis system block diagram. Experimental data from the NIF control system is automatically stored, processed and made ready for visualization following each pulsed laser shot.

SDA Framework

The data flow through the Analysis Engine starts at the Analysis Director, a Java-based application that processes data arrival events (both raw and intermediate analysis results). When data arrives, the Analysis Director schedules the appropriate analysis workflow request to the analysis engine input queue. The BPEL workflow processor then takes this request and performs four functions. It (1) orchestrates the sequence of analysis steps; (2) integrates, transforms, and transfers data between the various data repositories and the analysis modules; (3) schedules the appropriate analysis on the analysis servers using the adapter-in queue; and (4) retrieves their results using the adapter-out queue. The results are stored in a content management system archive.

The “pool” of analysis servers sit at the end of this pipeline. These servers monitor the adapter-in queue to receive “analysis invocation” messages. Each analysis server consists of two processes: a Java-based Analysis Adapter and an IDL server that runs the Analysis Modules. The “Analysis Adapter” provides the generic framework that interprets (adapts) an analysis request into an algorithm-specific IDL invocation. This analysis server pool consists of multiple computer processors, with multiple analysis servers running on each processor.

Analysis Modules

The Analysis Modules encompass a wide range of software systems that perform the actual signal and image processing and scientific data analysis on the shot-related data. These modules started out in a variety of forms—from a scientist’s laptop to full configuration management—and as diagnostic systems get commissioned, code is migrated to a common software

framework (documentation, version control, visibility to all users, etc.). Analysis Modules are specific to a measurement system, though the modules may share functionality between systems, components, and instruments (e.g., all streak cameras may share pre-processing software with different parameters).

For each diagnostic instrument there is a hierarchy of processing steps defined in the following way.

- “Instrument-level” processing corrects the signal of artefacts due to the measuring instrument such as a camera or oscilloscope. The output of this step is in instrument-corrected units such as pixels or voltage.
- “Diagnostic-level” processing transforms the data from the one or more instruments that comprise a diagnostic to deliver output in physical units (laser fluence, size in millimeters, etc.).
- “Campaign-level” processing combines data from one or more diagnostics to produce a physics result (e.g., many diagnostic sources are employed to determine the radiation temperature).

Storage and Visualization

The SDA Engine gathers data from the NIF repository and returns processed results to it. A separate web application called SADV (Shot Analysis Data Visualization) renders the results in a format defined by the users. By storing the data in a relational content management system, the data can be viewed in various ways. For example, the system is capable of tracking data metrics over time (trending) to detect systematic drifts that could affect data integrity. Comparisons to off-line data or simulations will also be supported. Expected results (and error bounds) will be compared to measured data as part of the analysis.

EXAMPLE DIAGNOSTIC

Dante [5] is a broadband soft x-ray spectrometer that is mounted on the NIF target chamber and measures such quantities as total x-ray flux (0.01 to 100 TW/sr), target radiation temperature (50 to 1000 eV), and energy conversion efficiency. Over the 20-ns that the target is irradiated by the NIF laser pulses, x-rays are generated by the target and captured by Dante. These x-rays are selectively filtered before the signals are acquired by 18 high-speed oscilloscopes. This allows Dante to measure time-resolved x-ray flux in different parts of the energy spectrum. Oscilloscope outputs and filter responses from all 18 channels are combined to “unfold” the radiation temperature and other quantities at each time step [6,7].

The analysis of the Dante data follows the methodology described in the last section. Instrument-level analysis consists of checking waveform integrity, correcting for background offsets and locating timing fiducials.

For Diagnostic-level analysis, the signal is re-sampled to a common time base and the voltage values are corrected to account for various components in the channel (attenuators, cables, splitters, etc.). The energy response spectrum for each channel (based on the types of x-ray diodes, filters and mirrors employed in the channel) is also calculated in this phase. Many of these components can change from shot to shot, so the Dante channel configuration and the calibration of each sub-component (over 100) must be accessible in the database, and validated by the responsible scientist, before the shot.

Finally, for Campaign-level analysis, the overall x-ray flux and radiation temperature is estimated by optimizing the modelled radiation spectrum relative to the measured values in each energy bin. Once all 18 channels have completed diagnostic level, the Analysis Engine launches the campaign-level modules to produce the final result.

It is important to report the statistical error bounds (one sigma) for each result. Uncertainty analysis is calculated at each processing step so that the error is propagated and can be displayed. The uncertainty is generally measured during the “performance qualification” phase of the diagnostic commissioning, where a series of test shots with expected outputs produce validation data. We expect that the performance of Dante, and similar diagnostics, will constantly be undergoing verification and validation to ensure that final results are publishable.

With such complex and extensive processing needs, and the importance of accuracy in reporting, data integrity is critical for all NIF diagnostics. Modern change-control policies and practices are required to ensure this integrity. The origins and “pedigree” of each data element is maintained, as well as that of all intermediate results. If a

procedure needs to be re-analyzed (say, a component is recalibrated), new versions of the results are generated. Calibration data is stored with start and end dates, so the effective value at shot-time is employed in the analysis.

SUMMARY

The most common expected use of this software will be that an experimentalist or the responsible campaign scientist will want to know the results of a NIF shot as soon as possible after a shot with the least time delay and the most confidence that the data received is ready for release. In the years to come, however, there will be many more use-cases for the software, including the diagnostic developers, laser scientists and others, so that as NIF evolves into a user facility, the SDA tools are expected to be employed in a variety of different ways. It is vitally important to the future of NIF that all shot-related data be processed and analyzed with a consistent method that is reviewed by scientific and engineering experts.

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