STATUS OF THE NATIONAL IGNITION FACILITY (NIF) INTEGRATED COMPUTER CONTROL AND INFORMATION SYSTEMS*

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Abstract

The National Ignition Facility (NIF) is operated by the Integrated Computer Control System in an object-oriented, CORBA-based system distributed among over 1800 front-end processors, embedded controllers and supervisory servers. At present, NIF operates 24x7 and conducts a variety of fusion, high energy density and basic science experiments. During the past year, the control system was expanded to include a variety of new diagnostic systems, and programmable laser beam shaping and parallel shot automation for more efficient shot operations. The system is also currently being expanded with an Advanced Radiographic Capability, which will provide short (<10 picoseconds) ultra-high power (>1 Petawatt) laser pulses that will be used for a variety of diagnostic and experimental capabilities. Additional tools have been developed to support experimental planning, experimental setup, facility configuration and post shot analysis, using open-source software, commercial workflow tools, database and messaging technologies. This talk discusses the current status of the control and information systems to support a wide variety of experiments being conducted on NIF including ignition experiments.

NIF OVERVIEW

The National Ignition Facility (NIF) is the world's largest laser system. The NIF laser consists of 192 laser beams which are housed in a ten story building the size of three football fields at the Lawrence Livermore National Laboratory (LLNL). NIF can deliver up to 1.8 million Joules and 500 Terawatts of ultraviolet laser light on to mm-sized targets centered in the ten-meter-diameter target chamber. Experiments using NIF's 192 laser beams are making significant contributions to national security, fusion energy, and basic science (Fig. 1).

During the last several years, a detailed set of experiments were performed as part of the National Ignition Campaign (NIC)— with an overall strategy for making a credible attempt for achieving fusion ignition, where more energy is created than consumed by the thermonuclear reaction, creating conditions similar to the core of a star [1]. While ignition has not as yet been achieved, steady process is still being made towards this goal. In addition to ignition experiments, a vast array of experiments devoted to stockpile stewardship and basic science have also been performed since NIF became operational in 2009. Since project completion, over 1,200 experiments have performed, all using the computer control and information systems described in this paper.

Figure 1: LLNL's National Ignition Facility is a stadium-sized facility housing the world's largest laser.

CONTROL SYSTEM OVERVIEW

NIF is operated by the Integrated Computer Control System (ICCS), which uses a scalable software architecture running approximately 4 Million lines of code on more than 1,800 front end processors, embedded controllers and supervisory servers. ICCS operates laser and industrial controls hardware containing 66,000 control and monitor points to ensure that all of NIF's laser beams arrive at the target within a 30 picoseconds of each other and are aligned to an accuracy of less than 50 microns, while assuring that a host of diagnostic instruments record data in a few billionths of a second. NIF's automated control subsystems are built from a common object-oriented software framework that deploys the software across the computer network and achieves interoperation between different languages and target architectures. Twenty-four hours a day, ICCS derives hardware settings from laser physics models, supervises shot setup and countdown; oversees machine interlocks to protect hardware, data, and personnel; provides operators with graphical interfaces for status and control; performs automatic beam alignment and wavefront correction; controls power conditioning and electro-optic switch subsystems; configures target diagnostics for recording X-ray, optical and nuclear phenomena; assesses shot outcome and archives shot data; and monitors the health of all subsystems and components. Automated control of NIF's 192 beams are overseen by 14 operator stations from a centralized control room, providing 24x7 nearly

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hands-off operation of shots cycle lasting 4-8 hours while at the same time assuring substantial machine safety and operational awareness.

ICCS is built from a common software framework which provides templates and services for the construction of software applications that communicate via CORBA (Common Object Request Broker Architecture). Object-oriented software design patterns are implemented as templates to be extended by application software. Developers extend the framework base classes to model the numerous physical control points and supervisory functions. About 140 thousand software objects, each individually addressable through CORBA, are active at full scale. Many of the objects have a persistent state that is initialized at system start-up and stored in a database upon a device change of state. Centralized server programs also provide additional framework services for client applications such as message logging, data archive, name services, events, alerts, reservations, and process management. A higher-level model-based, distributed shot automation framework also provides a flexible and scalable scripted framework for automatic sequencing of work-flow for control and monitoring of NIF shots [2].

NIF employs real time safety systems to monitor and mitigate the potential hazards in the facility. The Machine Safety System (MSS) monitors primary components in the facility to allow operations while also protecting against configurations that could damage equipment. The NIF Safety Interlock System (SIS) monitors for oxygen deficiency, radiological alarms, and controls access to the facility preventing exposure to laser light and radiation. Together the Safety Interlock System and Machine Safety System control permissives to the hazard-generating equipment and annunciate hazard levels in the facility [3].

Many instruments and detectors, oscilloscopes, interferometers, streak cameras, and other diagnostics-surround the target chamber to measure the experimental target phenomena. These phenomena are observed by a diverse suite of over fifty diagnostics including optical backscatter, time-integrated, time resolved and gated X-ray sensors, laser velocity interferometry, neutron time of flight, and diagnostics to diagnose fusion ignition implosion and neutron emissions. A Diagnostic Control System (DCS) framework for both hardware and software enables development of these target diagnostic systems. Each complex diagnostic typically uses an ensemble of electronic instruments attached to sensors, digitizers, cameras, and other devices. In the DCS architecture each instrument is interfaced to a low-cost Window XP processor and Java-based applications. Each instrument is aggregated with others as needed to the ICCS supervisory system to form an integrated diagnostic. The Java framework also provides data management, control and monitoring functions and graphical user interfaces [4].

CONTROL SYSTEM STATUS

During the past year, the control system was expanded to include a variety of new diagnostic systems including the Advanced Radiographic Capability (ARC), and programmable laser beam shaping and parallel shot automation for more efficient shot operations.

ARC will provide short (1-50 picoseconds) ultra-high power (>1 Petawatt) laser pulses used for a variety of diagnostic purposes on NIF ranging from a high energy x-ray pulse source for backlighter imaging to an experimental platform for fast-ignition. A single NIF Quad (4 beams) is being upgraded to support experimentally driven, autonomous operations using either ARC or existing NIF laser pulses. This significant effort to integrate the ARC adds 70% additional control points to an existing NIF Quad and is being deployed in several phases over this year, leading to automated ARC target shots controlled by ICCS during 2014 [5].

During the past year, several new target diagnostics have also been deployed using the DCS framework. For example, a new X-ray framing camera with improved temporal resolution (<10 ps) called DIagnostic X-ray Imager (DIXI) was developed to record the emission of X-rays from the target as a function of time. This diagnostic will be used to capture images of targets that undergo ignition and thermonuclear burn. [6].

The programmable spatial shaper (PSS) within the National Ignition Facility (NIF) has undergone major upgrades during this past year. This system reduces energy on isolated flaws in optics in order to lower the optics maintenance costs. To optimize laser performance and minimize operating costs for high energy laser shots, optic flaws are purposely locally shadowed, or blocked, from laser light exposure in the beamline optics [7]. These blockers temporarily shadow a flaw on an optic until the optic can be eventually be removed and repaired. This is accomplished by using a closed-loop system for determining the optimal liquid-crystal-based spatial light pattern for beam shaping and placement of variable transmission blockers over each flaw. This control system is currently being used and tested in the NIF. A combination of image analysis and machine learning techniques is also used to accurately define the list of locations where blockers should be applied [8].

Several major enhancements have also been made to improve overall shot efficiency. This includes being able to support parallel laser calibration and 192-beam target shots, parallel optic change-outs during shot cycle activities, as well an enhanced automation in target area activities including target and beam alignment. These enhancements resulted in several hours of operational savings for complicated cryogenic target shots.

Successful development and maintenance of the ICCS was a result of early adoption of rigorous software engineering practices including architecture, code design, configuration management, product integration, and formal verification testing [9, 10]. These processes are augmented by an overarching quality assurance program featuring assessment of quality metrics and corrective actions. An active program has also been underway for several years to analyse reliability and availability metrics and fix problems that have resulted in operational

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inefficiencies. This program has resulted in over a 40% reduction in problem logs reported for the ICCS system over the last two years.

Besides developing major new capabilities and improving reliability of ICCS, the control system has also been undergoing a major upgrade in hardware and software technologies. This includes a major upgrade of supervisory controls written in Ada and running on Solaris computers to Java processes running on Linux Virtual Machines [11]. This multi-year effort will be completed this year. Similarly, a major effort is underway in converting front-end processor Ada code running of VxWorks and Windows machines to Java running on Linux and Windows. Examples of each type of processor have already been deployed to the NIF, and will continue over the next several years. Since ICCS is a CORBA-based system, upgrades of individual subsystems written in different languages and operating systems can be staged over time, reducing the need for large-scale control system upgrades.

INFORMATION SYSTEMS OVERVIEW

An Information Technology (IT) infrastructure consisting of some 2,500 servers, 400 network devices and 700 terabytes of storage provides the foundation for NIF's control and information systems. A large suite of business and scientific support experimental planning, experimental setup, facility configuration and post shot analysis, and standard business services using open-source software, commercial workflow tools, database and messaging technologies has been developed.

NIF is composed of nearly 4 million individual components. Maintaining control of the physical definition, status and configuration of these components is critical to operation of the facility and validity of the shot experiment data. NIF has deployed a suite of business application software that provides an effective means of managing the definition, build, operation, maintenance and configuration control for all components [12]. Computer aided design (CAD) applications are used to generate models of individual components within the facility. The individual components are joined to create virtual assemblies for all NIF subsystems. These are created, maintained and change controlled through the Enterprise Configuration Management System (ECMS). An inventory management system (GLOVIA) keeps track of an inventory of all individual components and work orders for the NIF. The LOcation COmponent and Tracking and State Tracking System (LOCOS) tool provides users with the ability to understand the current state of installed components in the NIF, as well as providing various operational support capabilities such as problem logging issues, and managing and authorization of work in the NIF facility. Equipment maintenance for NIF's facilities management and operations organizations is planned and tracked through the System Maintenance & Reliability Tracking (SMaRT) system, where items requiring preventive, reactive and/or calibration maintenance are tracked to ensure readiness. Tools for tracking radiological and hazardous materials to ensure proper stewardship have also been developed.

Prior to NIF shots, the Campaign Management Tool Suite (CMT) provides tools for establishing the experimental goals, achieving reviews and approvals, and ensuring readiness for a NIF experiment. After each target shot at the National Ignition Facility (NIF), automated data analysis software provides results within 30 minutes from for over 50 target diagnostic instrument systems. A Shot Data Analysis (SDA) Engine based on the Oracle Business Process Execution Language (BPEL) platform has been developed for this purpose.

INFORMATION SYSTEMS STATUS

NIF's Information Technology (IT) team has focused on providing reliable network and computer resources by improving NIF ITs processes, architecture, and continuous monitoring capabilities. Over the past 36 months, NIF's infrastructure has been become more consolidated and segmented, and better engineered processes engineered processes have been implemented. NIF's supervisory control and business and experimental systems have migrated to virtualized server technologies. This was then followed by balancing and optimizing application resources such as CPU, memory, and IO, as well providing as a continuous monitoring of NIF IT resources [13, 14].

During the last several years, experimental support tools have focused on configuring the laser and diagnostics, and analysing and visualizing the data and results more efficiently. Over the last two years, CMT has significantly increased the number of diagnostics that supports to around 50 [15]. Meeting this ever increasing demand for new functionality has resulted in a design whereby more and more of the functionality can be specified in data rather than coded directly in Java. Support tools have been written that manage various aspects of the data and to also handle potential inconsistencies that can arise from this data driven approach. Templates for setting up diagnostics and the segments of the laser have also been developed to allow users to more efficiently setup the thousands of laser and diagnostics settings required for a NIF shot.

While the Shot Analysis and Data Visualization tools have been very powerful and flexible analysis product, it still required engineers very knowledgeable in software development practices to create the configurations executed by the SDA engine. To make analysis more user-friendly, the team took the approach of creating a tabular, database-based scripting language that allows users to define analysis configuration of inputs, input the data into standard processing algorithms and then store the outputs in a database. The creation of the Data Driven Engine (DDE) has substantially decreased the development time for new analysis and simplified maintenance of automated analyses [16].

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An experiment on the National Ignition Facility (NIF) may produce hundreds of gigabytes of target diagnostic data. Software teams developed tools for accessing data including a web-based data visualization tool, a virtual file system for programmatic data access, a macro language for data integration, and a Wiki to support collaboration [17].

In an experimental facility like the National Ignition Facility (NIF), thousands of devices must be maintained and commissioned during day to day operations. A suite of over 60 scripted maintenance and commissioning tools using Java and XML files have been developed to assist operators in performing repetitive and tedious operator functions, resulting in many hours of operational savings and reduced errors. These tasks range from quantifying the backlash of composite motors to realigning alignment light source beams back to target chamber center. For example, an MCT has recently been developed to compute the in-situ transmission of the 192 NIF Disposable Debris Shields [18].

Teams within NIF have documented hundreds of procedures, or checklists, detailing how to perform this maintenance. These checklists have in the past been paper-based. Software teams have developed the NIF Electronic Operations (NEO), which is a new web and iPad application for managing and executing checklists. NEO has increased efficiency of operations by reducing the overhead associated with paper based checklists [19].

CONCLUSION

The control system is being expanded to include a major laser system upgrade with an Advanced Radiographic Capability, as well as a variety of new diagnostic systems, and shot automation upgrades for more efficient shot operations**.** The control system is also undergoing a multi-year hardware and a technology refresh. Over the past three years, the IT infrastructure has become more consolidated and segmented and virtualized server architecture has been deployed. Tools have also been developed to more efficiently support business processed as well as experimental planning, experimental setup, facility configuration and post shot analysis. This has been accomplished while NIF experiments are run that support national security, fusion energy and basis science missions on a 24x7 basis.

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