IN THE MIDST OF FUSION IGNITION: A LOOK AT THE STATE OF THE NATIONAL IGNITION FACILITY CONTROL AND INFORMATION SYSTEMS

M. Fedorov, L. Beaulac, A. Casey, J. Castro Morales, J. Dixon, C. M. Estes, M. S. Flegel,
S. Heerey, V. Miller Kamm, B. Patel, M. Paul, N. Spafford, A. Barnes, V. Gopalan, R. Lacuata,
J. L. Vaher, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550

Abstract

The National Ignition Facility (NIF) is the world's largest and most energetic 192-laser-beam system which conducts experiments in High Energy Density (HED) physics and Inertial Confinement Fusion (ICF). In December 2022, the NIF achieved a scientific breakthrough when, for the first time ever, the ICF ignition occurred under laboratory conditions. The key to the NIF's experimental prowess and versatility is not only its power but also its precise control. The NIF controls and data systems place the experimenter in full command of the laser and target diagnostics capabilities. The recently upgraded Master Oscillator Room (MOR) system precisely shapes NIF laser pulses in the temporal, spatial, and spectral domains. While the increasing neutron yields mark the NIF's steady progress towards exciting experimental regimes, they also require new mitigations for radiation damage in control and diagnostic electronics. With many NIF components approaching 20 years of age, a Sustainment Plan is now underway to recapitalize NIF subsystems, including controls hardware and software, to assure operations through 2040. Keywords: fusion, ignition, status, upgrade, long-term support.

INTRODUCTION

The National Ignition Facility is a large (3 football fields) and complex (192 laser beams) experimental physics system (Fig. 1) [1]. Experiments at NIF support several programmatic missions: Stockpile Stewardship, Discovery Science, National Security Applications, and Inertial Confinement Fusion (ICF). For ICF, thermonuclear ignition has been the long-term goal of the facility, defined by the U.S. National Academy of Sciences as producing more energy from the DT target fusion than the laser energy on the target. The NIF was pursuing the ignition goal for almost 10 years, and it proved to be a scientific and engineering challenge.

Figure 1: NIF building layout.

A breakthrough was achieved in December 2022, when an experiment at NIF produced 3.15 MJ of fusion energy, more than the laser energy on the target of 2.05 MJ [2], thus achieving the fusion ignition. The achievement was broadly covered by scientific and news media, Fig. 2.

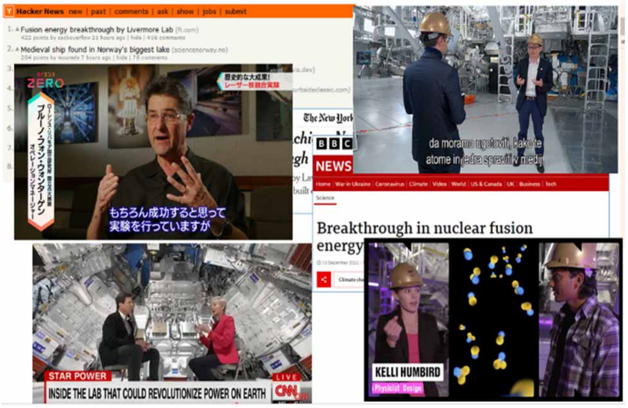

Figure 2: NIF Ignition covered by the news media.

NIF is operated 24x7 by a shift of the 12-14 Control Room operators with the help of the Integrated Computer Control System (ICCS). Over 66,000 devices with rich APIs are distributed over 2,300 front-end-processors (FEPs) and embedded controllers (ECs). NIF experiments are structured around laser shots. Each shot takes 4-8 hours and involves the control system executing over 2 million device operations.

ROLE OF CONTROL SYSTEMS

The NIF has achieved its remarkable fusion ignition results due to its precise control over energy, optics, and target parameters. This report highlights the pivotal role of control systems in ensuring the success of NIF's experiments. Figure 3 illustrates the multitude of parameters which are controlled and monitored by NIF systems.

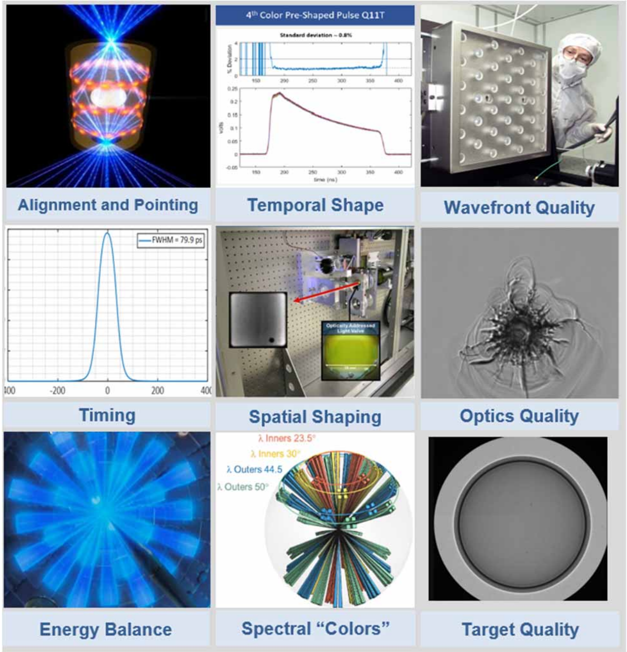

Figure 3: Energy and matter properties controlled by NIF.

Beam Pointing, Timing and Energy Balance

To deliver its energy, NIF relies on 192 laser beams, each requiring pinpoint accuracy within tens of micrometers (Fig. 4). These beams must converge at precise spots on the inner surface of the hohlraum. Laser pulse durations are mere nanoseconds, and they must reach the target with a tolerance of tens of picoseconds. Maintaining energy balance among the laser beams is vital for capsule compression symmetry, both in terms of overall energy and momentary power distribution throughout the pulse.

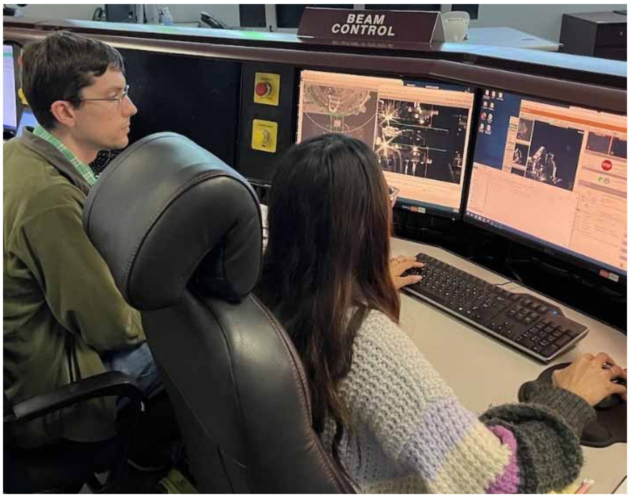

Figure 4: NIF Beam Controls operators perform laser beam pointing with ICCS Automatic Alignment software.

New Pulse Shaping System

The High-Fidelity Pulse Shaping System (HiFiPS) represents a significant enhancement in NIF's laser capabilities. This advancement ensures precise pulse shaping over several nanoseconds, alignment the pulse with the specified experimental configuration. Recent experiments underscore the critical role of precise pulse shaping in achieving optimal implosion symmetry, with the HiFiPS achieving better than 0.5% RMS shaping error and 2-3-fold improvement in shot-to-shot pulse shape reproducibility, Fig. 5. For an in-depth analysis of pulse shaping challenges and solutions, refer to Gowda ICALEPCS'23 paper [3].

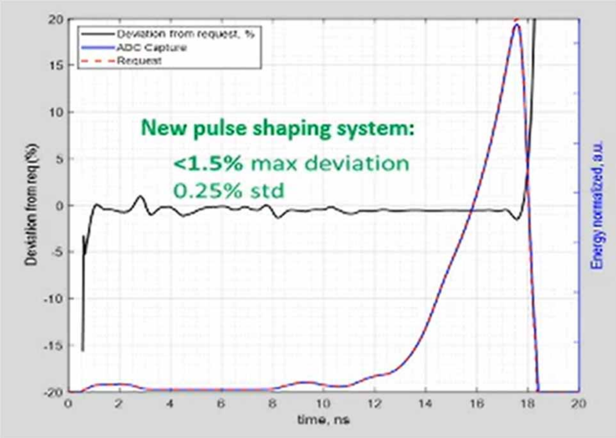

Figure 5: HiFiPS precision has improved significantly over the legacy system 5-20% deviation.

Enhanced Spatial Shaping: Gray Blockers

The NIF Programmable Spatial Shaping system (PSS), initially developed in the 2010s, plays a pivotal role in optimizing the performance of NIF amplifiers and optics, while simultaneously minimizing the risk of damage site formation. One key component of this system is the PSS mask, which precisely controls the energy distribution across the large 40x40 cm NIF final optics. This meticulous adjustment ensures an even energy distribution, eliminating any undesirable high spots. Additionally, the PSS blocker selectively protects optics locations where potential damage has been previously detected by the Final Optics Damage Inspection system (FODI).

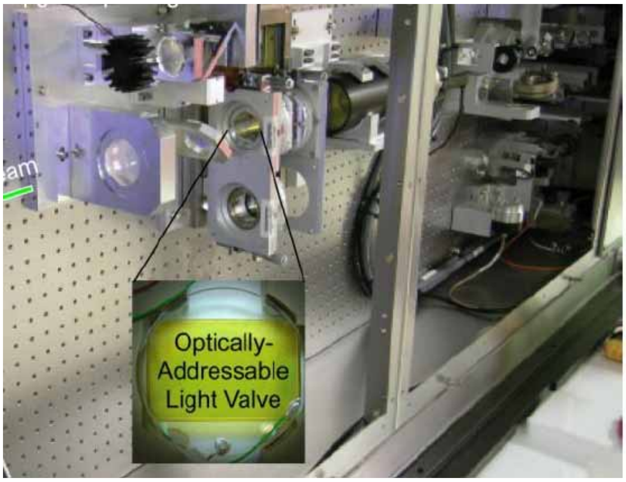

Figure 6: PSS in NIF Preamplifier Module (PAM).

The implementation of these features has been instrumental in enabling NIF to meet its original energy specification of 1.8 MJ, while significantly extending the lifespan and usability of its optics (Figs. 6-8). As NIF approached

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the final stages of achieving ignition, even minor increases in laser energy played a crucial role in surpassing critical thresholds. Notably, the adaptable control system of the PSS has facilitated the introduction of novel gray blockers and gray edge blockers. These innovations have further pushed the NIF's total energy capacity to over 2 MJ, effectively addressing and mitigating edge filamentation issues in the focus lenses [4].

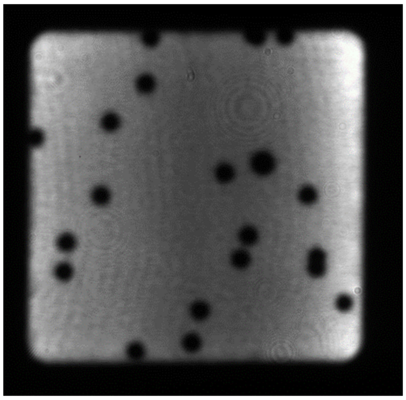
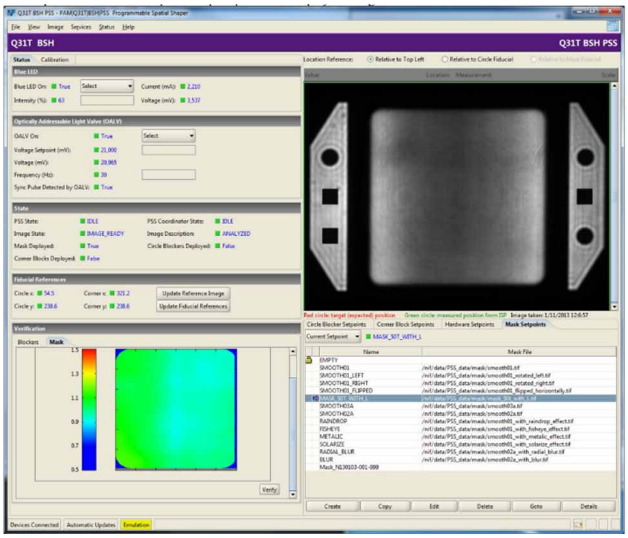


Figure 7: Laser beam with PSS blockers.



Blue LED

Blue LED On: True
Current (mA): 2,210
Intensity (%): 63
Voltage (mV): 3,537

Optically Addressable Light Valve (OALV)

OALV On: True
Voltage Setpoint (mV): 21,000
Voltage (mV): 20,965
Frequency (Hz): 30
Sync Pulse Detected by OALV: True

State

PSS State: IDLE
PSS Coordinator State: IDLE
Image State: IMAGE_READY
Image Description: ANALYZED
Mask Deployed: True
Circle Blockers Deployed: False
Corner Blocks Deployed: False

Fiducial References

Circle x: 54.5
Corner x: 321.2
Circle y: 238.6
Corner y: 238.6

Red circle: target (expected) position Green circle: measured position from ISP Image taken: 1/11/2013 12:6:57

Current Setpoint: MASK_30T_WITH_L

Name	Mask File
EMPTY	
SMOOTH01	/nif/data/PSS_data/mask/smooth01.tif
SMOOTH01_LEFT	/nif/data/PSS_data/mask/smooth01_rotated_left.tif
SMOOTH01_RIGHT	/nif/data/PSS_data/mask/smooth01_rotated_right.tif
SMOOTH01_FLIPPED	/nif/data/PSS_data/mask/smooth01_flipped_horizontally.tif
MASK_30T_WITH_L	/nif/data/PSS_data/mask/mask_30t_with_L.tif
SMOOTH03A	/nif/data/PSS_data/mask/smooth03a.tif
SMOOTH02A	/nif/data/PSS_data/mask/smooth02a.tif
RAINDROP	/nif/data/PSS_data/mask/smooth01_with_raindrop_effect.tif
FISHEYE	/nif/data/PSS_data/mask/smooth01_with_fisheye_effect.tif
METALIC	/nif/data/PSS_data/mask/smooth01_with_metalic_effect.tif
SOLARIZE	/nif/data/PSS_data/mask/smooth01_with_solarize_effect.tif
RADIAL_BLUR	/nif/data/PSS_data/mask/smooth02a_with_radial_blur.tif
BLUR	/nif/data/PSS_data/mask/smooth02a_with_blur.tif
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Figure 8: Control System UI panel for PSS.

Flexible Color Mapping

In conjunction with the addition of the fourth master oscillator, the NIF has expanded its control system infrastructure to accommodate this new component seamlessly. This expansion ensures that the new color is integrated with the same precision and reliability as the existing colors, maintaining the facility's reputation for robust performance.

To enhance the versatility of the laser system, the Flexible Color Mapping (FlexCM) system was introduced, Fig. 9. This switchboard allows researchers to configure the laser beams in different ways for their experiments. Importantly, the control system diligently verifies that the correct colors are directed to the intended laser cones, ensuring precise and consistent experimental setups. These developments collectively enhance NIF's capabilities, supporting a wide range of scientific research across various fields.

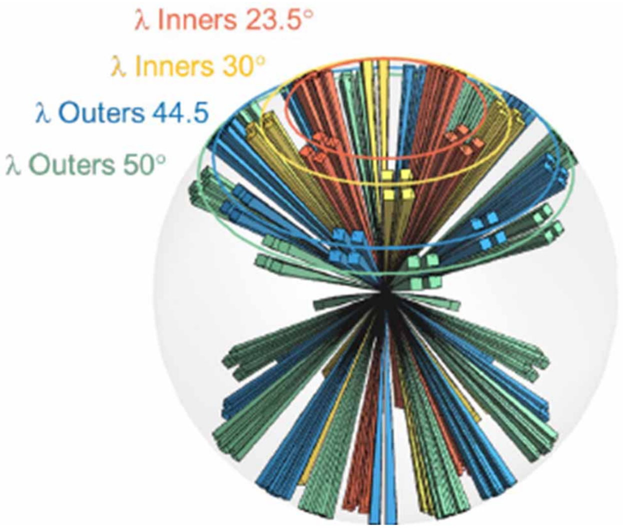

Figure 9: New 4th laser wavelength "color" added.

Quality of Beam Wavefront

One of the desirable characteristics of high-quality collimated laser beams is the flatness of their wavefront. Such beams can be precisely and predictably focused into a laser spot according to experimental requirements. Unfortunately, imperfections in optical components introduce irregular phase delays across the beam plane, distorting the wavefront.

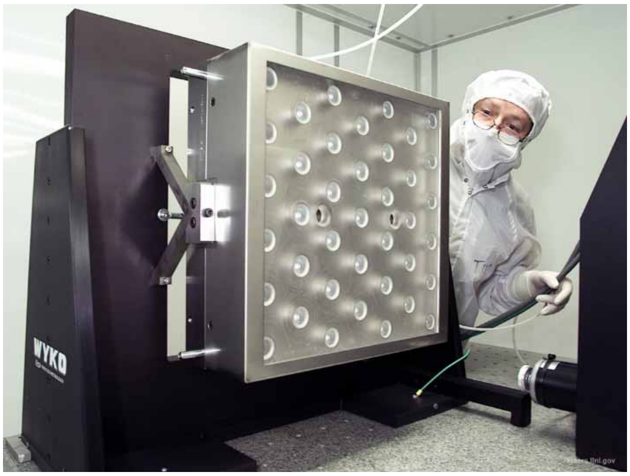

Figure 10: NIF Deformable Mirror

Eliminating all these irregularities would render these components prohibitively expensive. Moreover, some distortions change based on mechanical or temperature factors. This is precisely the scenario during a NIF laser shot when light from powerful flashlamps both heats and deforms the laser slabs in the amplifiers.

To address these challenges, NIF employs an adaptive optics wavefront control system. This system includes a deformable mirror with 39 actuators and a Hartmann sensor for each of the 192 beams, Fig. 10. The integrated hardware-software adaptive optics setup serves several functions. Primarily, it ensures the desired flatness of the wavefront during a system shot. Additionally, the system measures wavefront distortions to gauge the system under various conditions. By leveraging accumulated data, the control system can compensate for distortions induced by flashlamps and other similar factors. The software system's flexibility allows it to implement multiple correction strategies. For instance, when aligning the laser using low-power light propagation where flashlamp effects are absent, a different correction strategy can be applied.

Quality of Optics

To achieve its mission goals, NIF has to routinely operate at ultraviolet light fluences above damage threshold of optical glass and fused silica. In addition to continuous efforts to develop more damage resistant optics, NIF has employed optics recycling loop to keep damage growth in check. The laser beamlines were designed with removable modules which allow optics exchanges. It is then necessary to promptly identify the optics which develop potentially problematic defects so they can be removed, repaired, and reused later.

The optics recycle loop starts with ICCS Optics Inspection application which commands the Final Optics Damage Inspection (FODI) camera and associated motion and illumination controls to acquire images of optics (Fig. 11). The potential defect sites are automatically identified with machine learning algorithms [5].

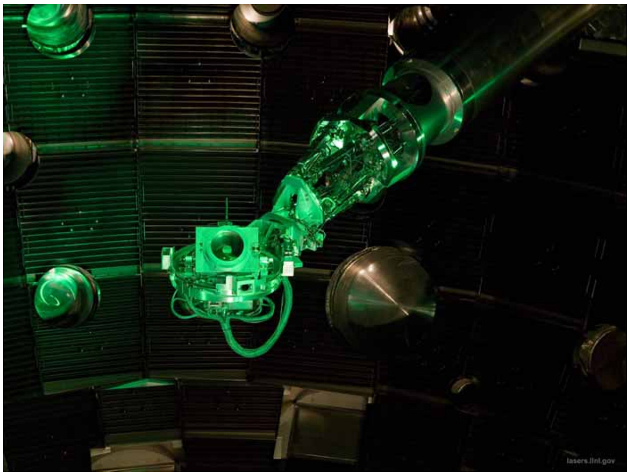

Figure 11: FODI Camera at NIF Target Chamber.

The entire lifetime of each of the 9000+ optics from its arrival from the manufacturer until the retirement is stored in the extensive Oracle database. The database includes metrology, qualification, and installation data, monitoring of the damage sites, removal, and repairs. The knowledge of defect growth history is essential for eliminating the false positives. For more in-depth ICALEPCS'23 presentation, please see Clark's [6].

Quality of Targets

Even minor imperfections in the target capsule shape or inclusions of foreign material can ruin an ignition experiment. A new Target Factory data system is being developed to comprehensively capture and study all contributing factors affecting the quality of the targets. In the meantime, besides the capsule, which is manufactured using advanced but still conventional means, the key component of the target is a delicate layer of Deuterium Tritium (DT) ice frozen on the inner surface of the target capsule. The formation of these layers happens in-situ, just hours before the ignition experiments. A sophisticated control system applies flexible layering recipes to form the DT layers, adjusting several control points with millikelvin precision, and using three-directional x-ray imaging system as a feedback, Fig. 12 [7].

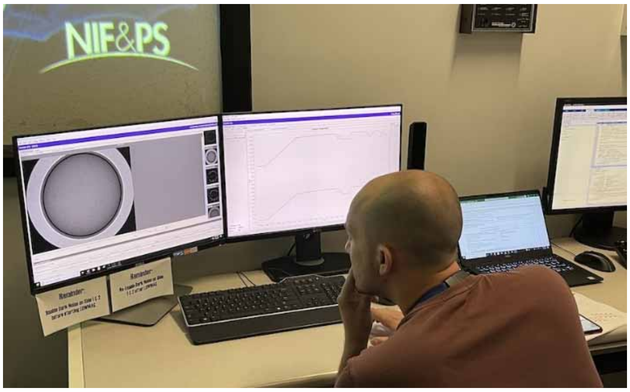

Figure 12: Operator monitors formation of the DT ice layer by ICCS cryogenic controls software.

NEW CHALLENGE OF HIGH NEUTRON YIELDS

While achieving Ignition opens exciting new possibilities for NIF experimenters, it also presents new challenges for Control System engineers (Fig. 13). Neutron radiation is damaging to electronic components, and it is difficult to shield. Key alignment and diagnostic systems are mounted directly on the NIF target chamber and are now subject to neutron damage.

Figure 13: Massive concrete-filled Target Bay doors are opened after a high-yield experiment, under stringent radiation survey protocols.

Plans are underway to design and build next generation of these sensors (such as CIVS, Fig. 14), taking advantage of newly available radiation hardened electronics, as well as making the sensors easily replaceable.

Figure 14: Cameras of the Chamber Interior Viewing System (CIVS) are mounted directly at the Target Chamber ports and subject to neutron radiation damage.

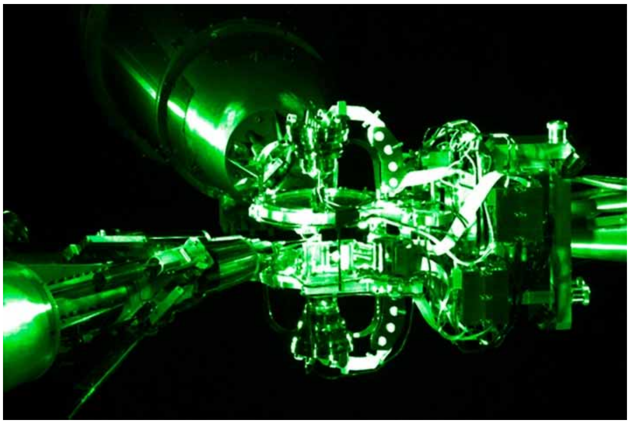

Figure 15: NIF Target Alignment Sensors (TAS) during target alignment at the Target Chamber Center.

The NIF Target Alignment Sensor (TAS) (Fig. 15) represents special challenge due to its critical importance for target alignment and beam pointing. Precisely calibrated both off-line and in-situ, the sensor cannot be easily repaired. The TAS can be removed from its positioner and stored in shielded location during the experiment, however its reinstallation currently involves a lengthy 72+ hours calibration procedure. (Fig. 16)

The NIF ICCS software controls team is transforming the manual multi-step calibration checklist into an automated process which will shrink the recommissioning time by a factor of 5-7 and thus allow to remove and reinstall the TAS between high-yield experiments.

Figure 16: NIF TAS is being removed from the positioner for maintenance.

LONG-TERM SUSTAINMENT

Increased frequency of failures of aging hardware, obsolescence of computing and IT platform require continuous maintenance and recapitalization efforts to keep NIF operational at its planned experimental capacity.

By 2023, the NIF controls teams have successfully completed several major modernization efforts, all while keeping the facility 24x7 operations on track [8]. The control system software was ported from the original Ada 95 programming language to Java. The Front-End-Controls processors migrated from PowerPC/VxWorks architecture to Intel/Linux. Most recently, the numerous video acquisitions systems have moved from proprietary Windows platforms to open-source Linux.

Figure 17: Maintenance of NIF diagnostics and cables in a switchyard rack.

These efforts to continue, to assure NIF operations through 2040. In the hardware area, the ongoing efforts are to replace the aging power supplies, oscilloscopes, and gas pressure gauges. Industrial, safety and access controls systems are getting refreshed from early 2000s technologies to modern Ethernet based infrastructure, Fig. 17 [9].

Numerous NIF embedded controllers continue to present a special challenge due to variety of board designs and operating system choices accumulated over the years. We are proceeding with a risk graded approach, focusing first on the systems with the most limited spares availability and critical to system operations.

Figure 18: Master Oscillator Room (MOR) embedded systems are upgraded for High-Fidelity Pulse Shaping.

Some systems will be migrated to a new embedded platform, while for others we have chosen to regain confidence by employing modern automatic build, test, and Continuous Integration (CI) process, Fig. 18, [10].

CONCLUSION

The NIF team recently achieved Fusion Ignition in laboratory conditions for the first time, marking an exciting milestone. This success, attributed largely to the precise control over the NIF laser energy, optics, and targets, emphasizes the significant contributions of the hardware and software controls teams across various intricate systems. As the NIF embarks on experiments with higher neutron yields, there is a pressing need to address the radiation effects on electronics, in addition to the ongoing efforts to update aging hardware and software systems.

ACKNOWLEDGEMENTS

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