Precision Surveying of the National Ignition Facility

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I. Overview of NIF

The world's largest laser, the National Ignition Facility (NIF), presently being constructed in Livermore, CA will contain 192 laser beamlines of 40cm-square aperture housed in a building 200 m long x 100 m wide x 30 m tall. Arrayed along each beamline are more than 40 optics that must be positioned to stringent tolerances. Precise positioning of the main beamline optical components is necessary to maintain the laser's clear aperture; sized to deliver the required power and energy. Non-optical components and structures also have ambitious alignment requirements. Achieving this requires the establishment of a very large virtual coordinate measurement machine.

The laser design severely constrains the solution. The laser optics must be kept very clean and the laser light is a hazard so all the beams and optics are enclosed for cleanliness and safety. To improve the cleanliness the optics are inserted into the enclosures from below which puts the bottom of the laser approximately 3m and in most places 5m above the floor. Many components must be surveyed looking nearly straight up. Provisions are required to survey into the opaque beam enclosure using high quality windows. The glass must be accurately fabricated and characterized and the refraction modeled and compensated.

The components are distributed throughout five building-sized rooms. Walls separating the rooms severely limit the lines of sight between the rooms. Two of the rooms are 30m cubes and have hardware on four different floors. One room is a 30m diameter cylinder 30m tall. It contains the target chamber and is where all the lasers converge. This room has equipment on seven floors. In these multi-story rooms, the control network must be run vertically to connect the various floor levels.

The target chamber is a 10m diameter sphere with 72 ports through which the lasers enter. The ports must be accurately placed on the sphere and their mounting flanges accurately oriented normal to the radial.

Presently the target chamber has been installed in the building where it will be completed and aligned. Installation of the other laser hardware begins this fall (1999) and will take until 2003 for completion. The first phase of hardware installation requires only rough alignment. Fine alignment to the specified tolerances begins next spring (2000).

II. Alignment Requirements

Many of the optics are sized to allow +/-3mm lateral (transverse to the laser axis) misalignment. Some optics such as lenses, pinholes at the lens' foci, and alignment light sources must be positioned to +/-1mm laterally. Some of the lenses must be positioned to +/-1mm longitudinally also.

In general the alignment tolerance is evenly allocated between the Line-replaceable Unit holding an optic and the kinematic mount that locates the LRU in the laser. For optics that have +/-1mm tolerance, their kinematic mounts are allocated +/-0.5mm. These are limit values and have been interpreted as 3-sigma values in the statistical analysis.

III. Alignment Strategy

Most of the laser was designed using a CAD system using a Cartesian coordinate system. Alignment merely requires an equivalent coordinate system be physically established in the building and the hardware put at the design coordinates. (The rest is left to the reader as an exercise.)

The decision to use a control network and align each component to its design coordinates was made after considering several other concepts. The concept we had the hardest time convincing the laser engineers would be a mistake was that of boresighting. This would involve some variation on sitting at one end of the laser and looking at crosshairs on each optic down the laser. In theory, superimposing the crosshairs would assure alignment. However, there are many reasons this would be unworkable. At best, boresighting provides only lateral alignment. Most of the NIF hardware has longitudinal requirements and much does not lie along the laser axis. Also boresighting is not very flexible. We do use boresighting in certain applications – primarily the alignment of rails and tracks.

For the method chosen, specific points (fiducials) are defined on each component and their "global" coordinates and tolerances specified. Relative coordinates and tolerances are also specified where appropriate. By placing each point at its defined coordinates within the allowable error bars it is assured that each component is properly positioned and aligned (with some exceptions for pointing). This strategy requires the establishment of an accurate Cartesian coordinate system, and techniques to measure the location of fiducials within that coordinate system.

The thousands of different parts each have a few to tens of points producing a total of tens of thousands of discrete points (some physical and some theoretical) which must be tracked over the life of the facility.

Specification of the desired design coordinates cannot be done accurately by manual or spreadsheet calculations. To date more than 90% of all manually specified coordinates contain at least one error. Improper specification of coordinates would result in hardware being precisely positioned at the wrong location. A method has been developed to calculate the design coordinates using simplified CAD models containing laser points of interest (beam centerlines, etc.) and fiducials. The models are mated in CAD to a skeleton and the fiducial coordinates are output in electronic files that are downloaded into surveying instrument computers.

Generally measurement (including surveying) concentrates on determination of the best estimate of a value. For the NIF project we have devoted almost an equal amount of effort toward quantification of the error bars about the best estimate value. Uncertainty constitutes approximately half the job. Measurement geometries are analyzed in advance (pre-analysis) and the results are used to refine the design and measurement plan. Tests are run to validate the assumptions used in the predictions. Finally actual measurement data is thoroughly analyzed both for self-consistency (best-fit residuals) and against the predictions to detect improvements or degradations.

IV. Measurement Methodology

A. Planning

Planning this work began at the end of the conceptual design phase of the project. This was a fortunate decision. Even with the relatively advanced start we have played catch-up since. Unfortunately most of the engineers could not bring themselves to factor alignment concerns into their designs until the designs were far into detailed design. So far, our overall strategy has been sufficiently flexible to accommodate the late definition (and re-definition) of requirements.

While the majority of NIF engineers are focused on the near-term installation, the alignment strategy has been developed to support the long term needs of NIF. The alignment tolerances are very small compared to the anticipated building motion so realignment is highly probable. Measurements will be needed throughout the 30 year life of the facility probably starting just after the first laser becomes operational. The facility's scheduled and unscheduled maintenance downtime budget is very small. Measurements will need to be rapid and must not compromise the optic cleanliness.

B. Control Network

The backbone of the measurement system is a control network of thousands of survey targets. The positions of the monuments relative to each other is measured, then a Cartesian coordinate system is superimposed over the monuments and coordinates assigned to each monument. Because the measurements are imperfect the true position of any monument can only be estimated within error bands. Our goal is to assign coordinates to an accuracy of +/-0.300mm 3-sigma. With minor exceptions, this allows the measurement of the coordinates of a survey target anywhere in the building to a 3-sigma error of +/-0.500mm relative to the absolute Cartesian coordinate system.

Control networks gain accuracy much like trusses gain stiffness through "depth of section". Typically networks can be relatively stiff horizontally because targets and instruments can be placed throughout the area and interconnected. However the NIF network is weakest vertically since in the laser bays instruments are generally confined to zone no more than about 3m above the floor. It is difficult to stiffen this by triangulation or trilateration. The network is similar to a sheet of paper; stiff in plane (horizontally) and flexible out of plane (vertically).

1. The Role of Gravity and Uncertainty in the Geoid

One way to stiffen the network vertically is by referencing gravity. Over small areas a precision level can provide a very accurate horizontal reference plane. NIF is large enough that the curvature of the earth must be accounted for. An imaginary horizontal plane tangent to a perfect earth at the target would be more than 2 mm above the earth at the other end of the laser bay. Total stations and levels generate a reference surface parallel to the earth. To correct this to a pure Cartesian plane it is necessary to know the local curvature very precisely – whether the local curvature actually is known accurately enough remains unresolved.

Earth curvature also affects the networks on the various floor elevations. Vertical lines at each corner of the building diverge significantly over the height of the building when compared to the control network accuracy requirements.

2. Free Adjustment

The control network does not have a "golden" monument. Instead the network is measured and then a coordinate system superimposed over the network. The superimposition can have six degrees of freedom. After the network has evolved sufficiently and a significant amount of hardware installed, it is desirable to hold the coordinate system as stable as possible. If the coordinate system were tied to a fixed monument, any movement in that monument would change the values everywhere else. By leaving the network free the coordinate system stays fixed to the centroid of the network. Independent movement of any monument is detectable and quantifiable.

3. Free-centering

Unlike traditional surveying where instruments are force-centered (setup directly over monuments), we set-up away from monuments and then accurately determine the instrument location by measuring position relative to the monuments. This eliminates centering errors. Similarly the precision spherical targets nest into conical seats for good repeatability.

4. Network motion

Measurement of the network is made more difficult because the building moves. Monuments are installed in the concrete foundation slabs (1 – 2m thick) and walls (in some places 4m thick). No monuments are used on the massive steel columns framing the building because they have too much diurnal and seasonal motion. Over the course of the past year the 100m-long target building slab shrank 25mm in length. Vertical deformations are anticipated also.

5. Lines of sight

One reason survey planning needs to start early is to establish adequate lines of sight for the control network. The building design led the laser design by approximately a year and was nearly complete before the survey planning started. Very late in the building design changes were made to provide vital lines of sight. Originally the walls between the laser bay and switchyards had no holes or doorways – doorways were added solely for surveying. Similarly holes were added to the elevated floors in the target bay to provide vertical sight lines for connecting the network between floors.

C. Instrumentation

State of the art instruments are not a factor of 10x better than the NIF measurement accuracy requirements. Meeting the requirements necessitates high accuracy instruments combined with explicit attention to quantifying their achieved accuracy. We promise our measurements to be accurate in three orthogonal dimensions to +/-20ppm of range (3-sigma). By measuring multiple targets from multiple stations that accuracy can be further improved.

The primary measurement instruments are Leica Total Stations, SMX Model 4500 Laser Trackers, and a Leica Model NA3003 Digital Level. Other instruments such as a Hamar Laser Plane Reference and a Quest "Euclid" Laser Line Reference are also used.

Total stations report elevation (more properly "zenith") and azimuth (horizontal) angles and range to target. Total stations are gravity referenced – the zenith angle is measured from the local gravity vector. The best total stations have accuracies better than +/-0.5 arc second (+/-2.5 microrad) in both angles, and better than +/-1mm range (values are specified at 1-sigma). Testing of Leica's current high-end guns (TCA 2003 and 5000) with Automatic Target Recognition (by which the instrument self-aims at the center of the target) reveals the ATR does not work well at ranges on the order of 20m or less. Also, the optics necessary for ATR appear to degrade the range accuracy from better than +/-0.2mm (TC 2002) to +/-1.0mm. The +/-1.0mm range error is adequate for construction but cannot be tolerated for the final control network and alignment. The 2002 and 2003 have the same performance specifications but while the 2003 just barely meets its range accuracy spec, the 2002 performs almost an order of magnitude more accurately. We limit the use of our 2003s to jobs where their in-accuracy is acceptable. For critical measurements with total stations we rent 2002s. Leica has discontinued the 2002s and they are only available second-hand.

We prefer servo-driven total stations over the manual models because of their increased speed in rough centering onto known targets. Typically manually acquired shots are needed to a few targets to orient the instrument, then the computer can drive the gun to the remaining targets with the operator only needing to fine tune the aiming just prior to each shot. All shots are made at least twice (direct and reverse face) from each setup and the servo greatly speeds the work. The servo also helps prevent misnumbering the targets.

Laser trackers are similar to total stations in that they both measure two gimbal angles and range. It is neither necessary nor possible to sight through a laser tracker to a target. Trackers are slightly worse than total stations in angle (although also less than +/-1 arc-second) and much better in range – typically a few ppm (close to interferometric accuracy). One significant advantage is their ability to measure in any attitude. They are not gravity referenced. They can measure targets directly up and down where total stations are limited to about 45 degrees above and below horizontal. Because the laser is overhead with access ports on the bottom side, most measurements must be made shooting nearly directly straight up. Another critical application for the tracker is measuring vertically up and down between floors in the switchyards and target bay to extend the control network to all levels. The tracker allows the establishment of a truly 3-dimensional network.

The primary targets are 1.5 inch diameter spherically mounted retroreflectors (SMRs). These are comprised of hollow hardened tooling balls with first-surface internal corner cubes set within less than 0.0005 inches of the ball center. The corner cubes must be very accurate – the incoming and outgoing beams must be parallel within 1-2 arc-seconds. In places where the standard SMR is too large to fit we use a 0.5 inch diameter SMR. Typically the balls are retained in conical seats with magnets on the axis of the cone. It can be very difficult to visually aim at the center of an SMR so total stations are aimed at 1.5 inch diameter hemispheres with bullseyes located at the center of the sphere. Once the gun is aimed, the bullseye is replaced with an SMR and the measurement taken. Aiming at the bullseye sets the two angles and the SMR allows accurate ranging. Laser trackers nearly always use SMRs although there are specialized targets for unique applications.

The Leica NA3003 digital level plays a key role. It must be rough leveled to get within the range of its compensator, then it is pointed at a vertical "rod" covered with bar code. The level can read the code to within a few microns. The level can be run down a course 100m and back and close to under 0.100mm. It is very fast and we rely on it to provide sufficient strength vertically for our network and as an efficient method to detect building motion (assumed to virtually always have a vertical component). The level is used also to orient a set of targets measured by a tracker, because the tracker has no gravity reference.

D. Software

Even the most basic construction surveying is computer-intensive. Software also plays a central role in designing the control network and measurement process, analyzing the measurements and archiving the data. For NIF we rely heavily on software developed at the Stanford Linear Accelerator Center for operation of the total stations, preanalysis (simulation) and analysis of the observation data. The SLAC software includes database capabilities. Our other primary program is the laser tracker software (which recently incorporated SLAC routines).

We have also developed custom software (mostly Microsoft Excel macros) to handle some of our unique needs. For example the target chamber center is defined as the center of the smallest sphere that intersects the centerlines of all the target chamber port flanges. We wrote a routine that accepts the survey data on the port flanges and calculates the location of the target chamber center and the size of the intersection sphere. Another area where our needs are apparently unique is in calculating best-fits from data. Typically best-fits try to minimize the root-mean-square error. If nine out of ten points are perfect and the tenth is off by 1.0, the best fit will adjust to move the nine points off by 0.1 and leave the tenth out by 0.9. For NIF the worst beam is the only one that matters. If the worst point is within specification, the others will be better. We frequently use custom best-fit routines that would leave all ten points in the previous example out by 0.5.

Our search for useable commercial software has not been fruitful. One good network analysis code (Star-Net) is limited by being constrained to a local gravity reference. It does not analyze arbitrarily oriented instrument axes (as for laser trackers). Brunson's Spatial Analyzer software can handle both total stations and laser trackers (and other instruments) and might be a good solution for anyone who cannot obtain the SLAC programs.

For nearly two years we have had one person working full time with the software (not writing it). We have just added a second data analyst to handle the surge of data that will occur as hardware starts being placed and aligned.

V. Closing

The measurement of NIF is a world-class challenge. There are thousands of items with stringent alignment specifications. The equipment is arrayed in ways that make accurate measurement difficult – spread over a large area, separated by walls and floors, enclosed in metal, placed overhead, etc. The control network accuracy requirements press at the limits of the most accurate gravity models available. The job could not have been done a few years ago – the technology is being developed simultaneously with our planning to use it.

The majority of our work to date has been preparation. Actual alignment work is now ramping up. The next several years will reveal the strengths and weaknesses of our preparation.