NITIM: A NEW METROLOGY MACHINE FOR TARGETS WITH HIGHLY VARIABLE GEOMETRIES

20th Target Fabrication Meeting
May 23, 2012

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Outline

• Background and Motivation

• Description of Machine

• Precision Engineering Design Principles
  — Error budget
  — Lumped mass dynamic model
  — Robust manual tip-tilt stage

• Measured Performance

• Summary
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TARGET: ASSEMBLY WITH TENS $\mu$m TOLERANCES

1. PHYSICS PACKAGE
   Central focus of experiment
   e.g. hohlraums, capsules, foams, laser alignment artifacts, etc.

2. PERIPHERALS
   Components that support experiment
   e.g. shields, backlighters

3. MOUNTING BASE
   Interfaces with the chamber’s target positioner

PURPOSE
- Fusion research
- High energy density physics research
- Basic science (astrophysics and materials science)
Correct spacing and alignment of the target components relative to one another is also crucial for experiment success and not damaging the system.

EXTREMELY HIGH POWER LASER BEAMS IRRADIATE THE TARGET
CHARACTERIZING TARGETS AS SEEN FROM PORTS ON THE CHAMBER IS NECESSARY

Verify alignment of peripherals to physics package

Verify angle and offset of peripherals from physics package

Verify orientation of components to diagnostic ports

Verify that shields are correctly positioned to protect sensitive diagnostics
Powell Scope was too small for NIF Targets

- Powell Scope is a successful, but small 5-axis optical measuring machine that the NITIM was designed to replace.

- NIF Target Peripherals (e.g. backlighters and shields) further from target chamber center (TCC)
  - NIF Targets: ±50mm
  - Powell Scope range: ±12.5mm from TCC

- NIF target length:
  - NIF: 170mm from base to TCC
  - Powell Scope: ≤92mm
We took the opportunity to implement other improvements

- 2 telecentric optical axes (orthogonal to one another) for convenience and verifying perpendicularity of target components
- 2 legs for each optical axis:
  - Zoom leg for flexibility regarding field of view and magnification
  - Fixed focal length leg that is more stable, for measurements
- Improved vibration isolation
- Significantly improved lighting
- Motorized control of all axes (1 manual axis on Powell Scope)
- Increased camera resolution
- Dual monitor setup and improved ergonomics
  - Viewports at eye level, so don’t have to hunch over
  - Keyboard tray
- Ability to easily incorporate optics to view the target base for relating measurements at TCC to the base datum
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Motion System

- X-Stage (100 mm)
- Y-Stage (100 mm)
- Z-Stage (100 mm)
- θ-Stage (240 deg.)
- φ-Stage (360 deg.)
Front Optics Support Frame
Front Optics System
Left Optics System
Design requirement is <10 μm positioning error within any 10x10x10 mm volume
Each optical axis has a fixed focal length camera, and a zoom leg to a camera and eyepiece

- Zoom leg is used for orientation and viewing fine details, but image moves on camera as the zoom is changed
- Fixed leg provides a measurement datum
Multiple illumination strategies allows measurement of complex targets with highly variable geometries

Vee-blocks are adjustable and lockable prevent measurement variation due to directional lighting changes
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An error budget guided the design process and informed key decisions

Motion Errors
(Displacement Error, Straightness, Flatness, Roll, Pitch, Yaw, Axial and Radial Error Motions, and Tilt Error Motions)

• Assembly Errors
  • Optics alignment
  • Stage squareness

• Deflections Due to Compliance

• Fabrication Errors (Tolerance stack up)

• Does not include thermal or vibration error sources
  - Sensitive measurements are relative to target center (not absolute)
  - Target is stiff and rapid settling time of system is not required

We used several error combinatorial rules to better predict the errors in the system

• Average of RSS and Sum – “AVG(RSS,SUM)” – reasonable estimate
• Central Limit Theorem (99%) – “CLT-E99” – reasonable estimate
• Central Limit Theorem (95%) – “CLT-E95” – more optimistic than CLT-E99
• Systematic vs. Random – “SvR” – reasonable estimate
The error budget identified the worst error culprits and we used that information to guide design decisions.

Predicted error in the X-direction from a 10 mm move in XYZ and 180° move in θ and φ

Error budget was used to:
1. Define minimum required stage accuracy
2. Define required tolerances of fabricated parts
3. Predict performance of completed system
A simple lumped mass dynamic model informed stage selection and predicted expected resonances

- Fast and intuitive estimate of the low mode rotational natural frequencies of the system
- Assumes rigid components and connections
- Combines all of the masses and positions into an equivalent mass and moment of inertia
The lumped mass dynamic model helped guide design decisions and predict the performance of the system.

<table>
<thead>
<tr>
<th>Conservative Estimate (Less Stiff)</th>
<th>about x-axis</th>
<th>about y-axis</th>
<th>about z-axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural frequency at θ-stage (Hz)</td>
<td>83</td>
<td>0</td>
<td>227</td>
</tr>
<tr>
<td>Natural frequency at Z-stage (Hz)</td>
<td>60</td>
<td>94</td>
<td>89</td>
</tr>
<tr>
<td>Natural frequency at X-stage (Hz)</td>
<td>25</td>
<td>27</td>
<td>79</td>
</tr>
<tr>
<td>Natural frequency at Y-stage (Hz)</td>
<td>23</td>
<td>24</td>
<td>64</td>
</tr>
</tbody>
</table>

Lowest natural frequency as measured by the feedback controller:

<table>
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<tr>
<th>About x-axis</th>
<th>About y-axis</th>
<th>About z-axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-stage $f_n$ (Hz)</td>
<td>54</td>
<td>-</td>
</tr>
</tbody>
</table>

The lumped mass model helped us determine that relatively little dynamic performance was gained by using significantly more expensive stages.
Manual tip-tilt stages were designed to align vision systems to motion system.

Tip-Tilt Actuators (3 Screws):

- 440 SST, 55 HRC
- 40 TPI

- Spherical bearing surface
- 0.75” Diameter → >20 kg load limit

Adjust tip-tilt with wrench or hex driver

3 Bal-Tec V-Grooves

SST, 58 HRC, ultrafine grain

3 aluminum clamps, each with 3 rounded feet, secure the optics to the frame.
The tip-tilt optics alignment stages used precision engineering principles to meet the design requirements.

- 6 µm optical resolution over 100 mm total travel → 60 µrad optics alignment requirement
- 40 TPI pitch, 200 mm distance, and 5° resolution → <45 µrad resolution

Decoupled tip and tilt motions
Flexures lock tip-tilt actuators
“Cookie bite” in plate thread gives 3-jaw chuck clamping
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A 20 mm artifact, located in the same position as a target, was measured with the X, Y, and Z stages.

<table>
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<tr>
<th>Error Budget Predictions</th>
<th>Measured Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AVG of RSS, SUM</td>
</tr>
<tr>
<td>X-Stage Error (µm)</td>
<td>4</td>
</tr>
<tr>
<td>Y-Stage Error (µm)</td>
<td>3</td>
</tr>
<tr>
<td>Z-Stage Error (µm)</td>
<td>2</td>
</tr>
</tbody>
</table>

The measuring error is in the range predicted by the error budget and combinatorial rules.

Characterization of errors from rotation stages and moving multiple stages at once is on going.
• A new 5-axis machine was designed and built to characterize targets for high-energy lasers
• Precision engineering principles that rely on determinism were used to guide the design
• The performance of the machine is consistent with the predictions of the design tools
Questions?