ERROR ANALYSIS FOR A HIGH-PRECISION FIVE DEGREE OF FREEDOM HYBRID MECHANISM FOR HIGH-POWER HIGH-REPETITION RATE LASER OPERATIONS

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Introduction

- A significant challenge, yet a fundamental requirement, for a high-power laser system is its ability of positioning and aligning a target at the laser focus with an accuracy of few micrometres (typically ± 4 µm) at a rate of at least 0.1 Hz (with plans for 10 Hz or higher in future).
- To meet the specifications for target positioning accuracy and target surface quality, the Central Laser Facility has designed and developed a new high-accuracy microtargetry system (HAMS) for accurate mounting and motion control of targets for the Astra-Gemini laser.
- HAMS has a hybrid kinematic structure, which consists of parallel and serial mechanisms. As with any other precision machine, this hybrid structure's performance can be affected by a wide range of errors, particularly geometric errors that arise from manufacturing and assembly faults.
- Identifying these sources of error to develop effective error compensation strategies is particularly important for the positioning and alignment accuracy of HAMS.

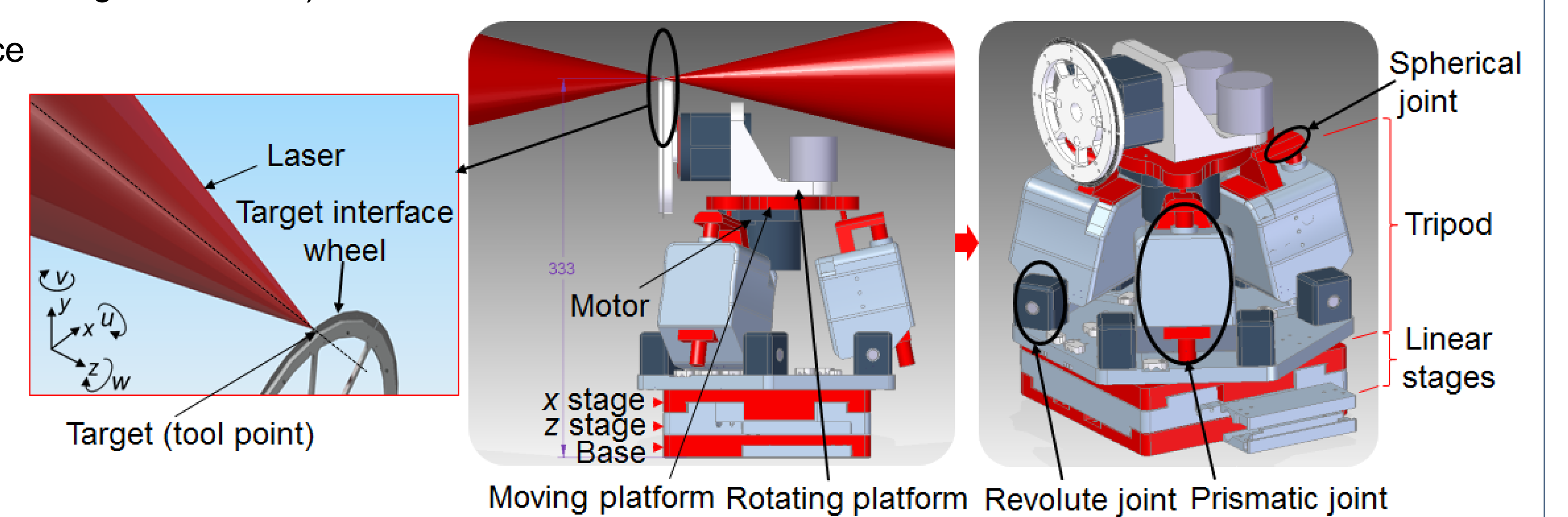

Figure 1. Laser-target interaction (L) and features of HAMS (M & R).

Objectives

- Analysis of error sources of HAMS to show how the errors affect the positioning accuracy of target during the target alignment process.
- Demonstration of a practical strategy of developing an error model for a hybrid structure.

Method

- Error model, using kinematic analysis, to derive analytical equations for the positional deviations of target (only parallel mechanism considered in this study).
- Interferometer (Renishaw model XL-80) to measure the linear displacements of the moving stage and the target.

Modelling

Kinematic structure

- Two degree-of-freedom (DOF) linear *xz* system: translations along *x* and z axes.
- Three DOF parallel link tripod and a motor mounted on the moving stage: rotation about *x* axis (called tip, *u*) and translational along *y* axis, and one further rotation about *y* axis (called tilt, *v*), respectively.
- The tripod can be described as a RPS system, where *R*, *P* and *S* denote revolute, prismatic and spherical joints, respectively.

Modelling technique

- 4×4 Homogeneous transformation matrices (HTM) to describe the spatial relationships of the coordinates, as shown in Figure 2, with respect to the reference coordinate.
- Loop closure equations, indicating by black and red lines in Figure 2, of the mechanism with and without considering the errors.
- Errors that come from generalised sources, i.e. geometric errors will have general effects on the error sources, rather than individual effects.

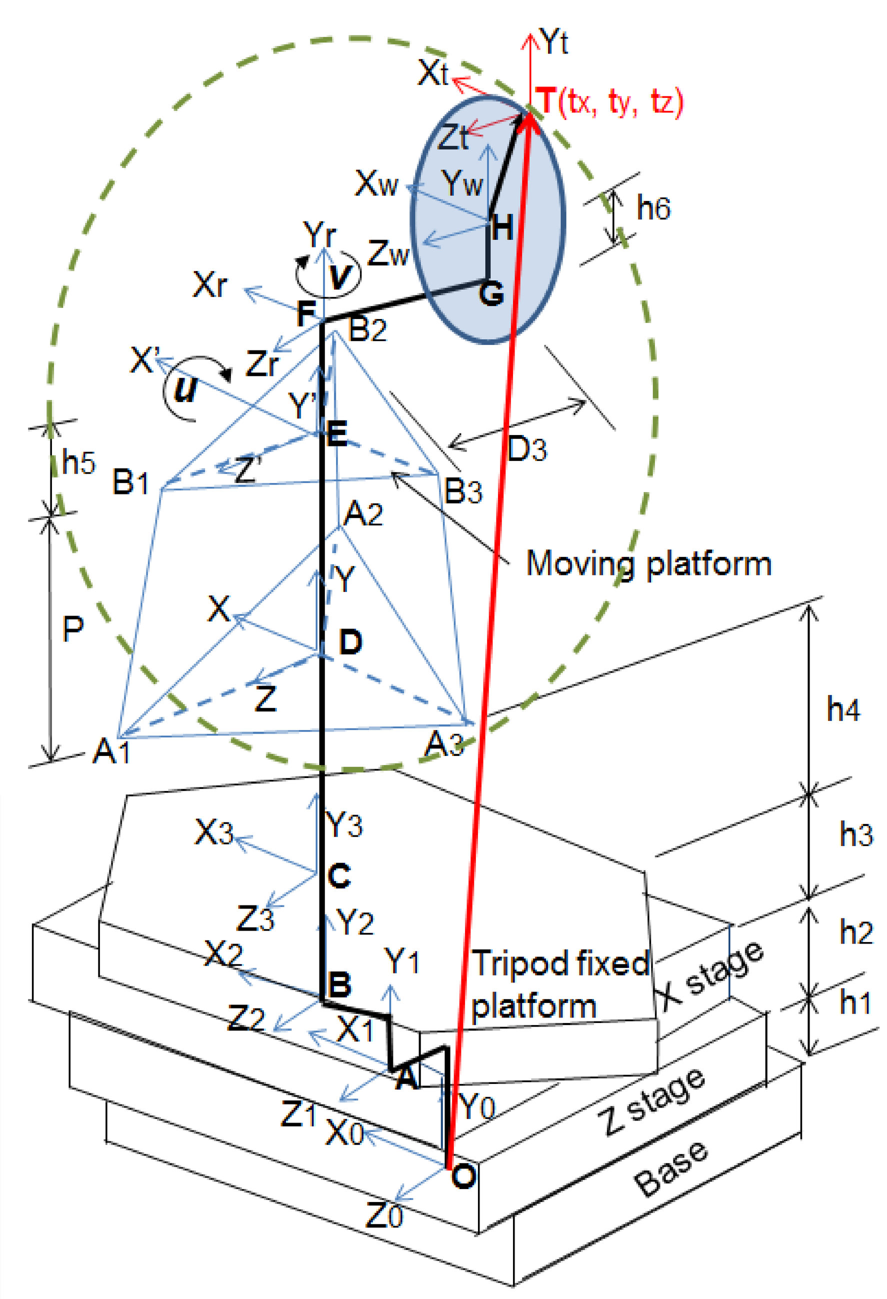

Figure 2. Schematic representation of the kinematic structure of HAMS.

Error definitions

Parasitic motions (tip error)

- A small amount of translational motions along *x* and z, and a rotation motion about *y* (Figure 3, L).
- Typical HTM to represent parasitic motions:

$$T_{tip\ err}=\begin{bmatrix}\cos u_{err} & 0 & -\sin u_{err} & \delta_{x_{err}}\\ \sin u\sin u_{err} & \cos u & \cos u_{err}\sin u & 0\\ \cos u\sin u_{err} & -\sin u & \cos u\cos u_{err} & \delta_{z_{err}}\\ 0 & 0 & 0 & 1\end{bmatrix}$$

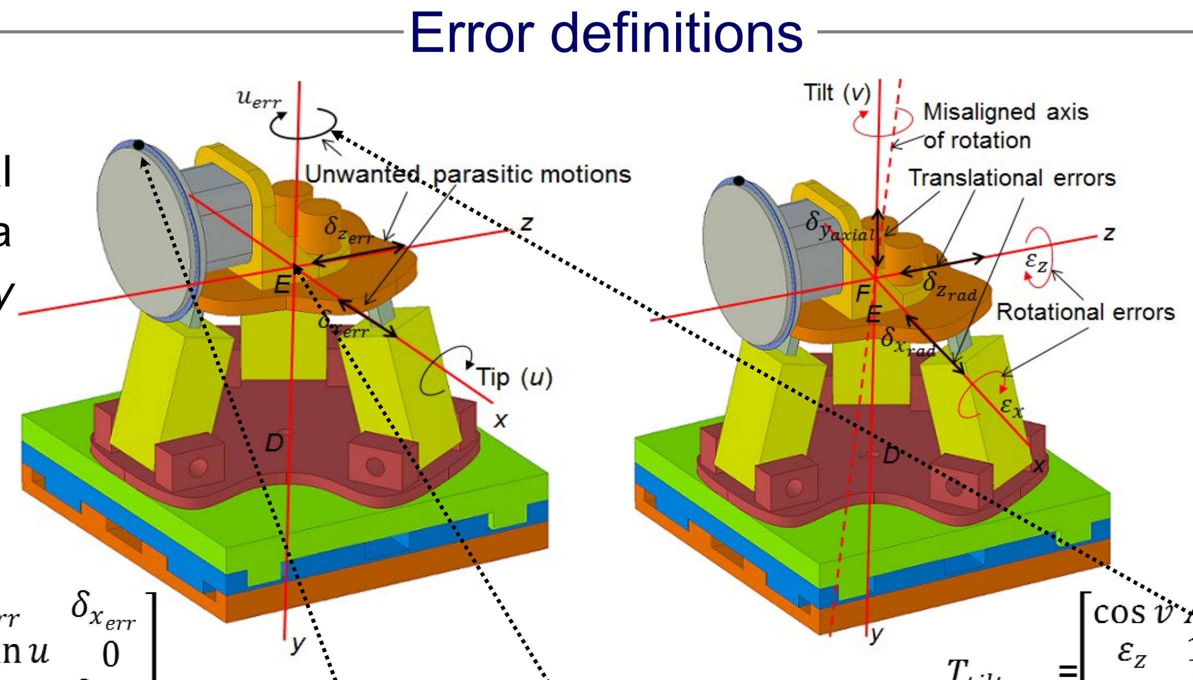

Figure 3. Tip errors (L); Tilt errors (R).

Misaligned axis of rotation motions (tilt error)

- Two radial and one axial error motions along *x*, *z* and *y* axes respectively, and two rotational error motions about *x* and *z* (Figure 3, R).
- HTM to describe these errors:

$$T_{tilt\ err}=\begin{bmatrix}\cos v & A & -\sin v & \delta_{x_{rad}}\\ \varepsilon_z & 1 & \varepsilon_x & \delta_{y_{axial}}\\ \sin v & B & \cos v & \delta_{z_{rad}}\\ 0 & 0 & 0 & 1\end{bmatrix}$$

where,
$A = (\sin v\ \varepsilon_x - \cos v\ \varepsilon_z)$ and
$B = (-\sin v\ \varepsilon_z - \cos v\ \varepsilon_x)$

Positional deviation, for instance, in z direction: $D_{zt_{tip\ error+arch}} = \delta_{z_{err}} - (h_5 + h_6 + t_y)\sin u + (d_3 + t_z)(\cos u\cos v\cos u_{err} - \cos u\sin v\sin u_{err}) + t_x(\cos u\cos v\sin u_{err} + \cos u\sin v\cos u_{err})$

Results

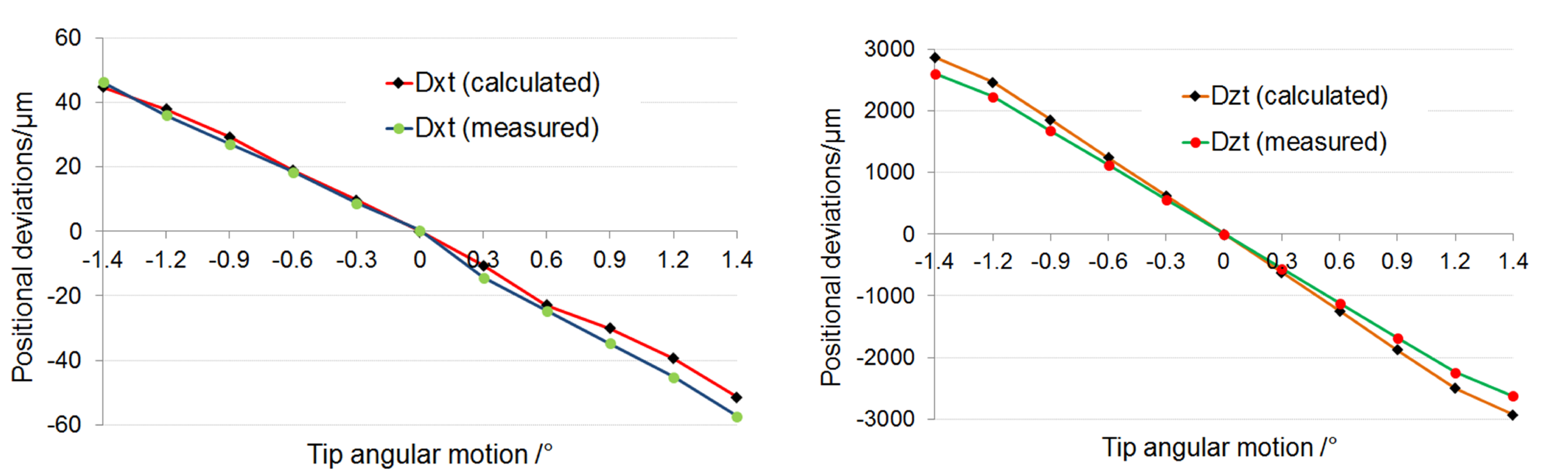

Figure 4. Comparison of the calculated and measured positional deviations of target in the x (L) and z (R) directions due to tip and its associated parasitic error motions*.

** overall measurement uncertainty from the repeatability of measured distances and from the laser interferometer ≤200 nm (coverage factor k=2, giving a confidence level of approx. 95%).*

- Tip motion and its associated error motions , if un-compensated, cause significant positional deviations at the target.
- These deviations are primarily due to Abbé offsets of HAMS in *y* and *z* directions.
- Linear displacements measured near the centroid of the moving platform represent two translational parasitic motions, $\delta_{x_{err}}$ and $\delta_{z_{err}}$,contributing to small positional deviations at the target.
- However, it is the parasitic rotational motion, u_{err} , that can have a considerable effect on the positional deviation of the target.

Conclusion

Some positional deviations of target arise from the errors that are originated from the kinematic nature of RPS structure of HAMS, while some positional deviations are results of the amplifications of the angular error by structural offsets of HAMS. Using these error motions of a parallel mechanism, instead of individual joint errors, have found to be effective in simplifying the error analysis and , hence, in developing an error model.