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Error modelling and validation of a high-precision five degree of freedom hybrid mechanism for high-power high-repetition rate laser operations☆

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ABSTRACT

The accuracy, repeatability and speed requirements of high-power laser operations demand the employment of five degree of freedom motion control solutions that are capable of positioning and orientating the target with respect to the laser(s)-target interaction point with high accuracy and precision. The combined serial and parallel kinematic (hybrid) mechanism reported in this paper is a suitable candidate for this purpose; however, a number of error sources can affect its performance. A kinematic model to analyse the errors causing the positional and orientational deviations of the target is described considering two rotational degrees of freedom of the hybrid mechanism. Strategies are outlined to simplify the error analysis and to determine the error parameters of the mechanism using the error model and an experimental technique.

1. Introduction

Pulsed lasers with high power (petawatt class lasers) have seen significant development in the last few decades. High-power lasers are used for advanced research activities in physics, chemistry and biology, for example, to accelerate subatomic particles to high energies, to study biochemical and biophysical processes, and for cutting-edge applications, such as fusion energy, radiation therapy and secondary source generation (X-rays, electrons, protons, neutron and ions) [1–3]. To utilise the full potential of high-power lasers, large-scale facilities need to operate at high-repetition rates, which presents many engineering challenges [3,4]. One such challenge is the positioning and aligning of a micro-scale target (or in short ‘target’) relative to the focus of the laser beam(s) with an accuracy of few micrometres - a fundamental requirement for a high-power laser-target interaction to ensure that targets are reproducibly accessible to the highest intensities available, that is in the region of the laser beam focus as determined by the Rayleigh range [5,6]. Fulfilling this requirement for a high-repetition rate laser system means that new targets have to be positioned and aligned at the laser beam focus at a rate of at least 0.1 Hz (with plans for 10 Hz or higher in future) [4–6]. To meet the specifications for target positioning accuracy and to achieve the required speed of high-repetition rate laser operations, the Central Laser Facility (CLF) has designed and developed a new high-accuracy microtargetry system (HAMS) for mounting and motion control of targets for the Astra-Gemini high-power laser [7,8].

HAMS is based on a tripod architecture mounted on a two-axis linear stage, providing control of all five degrees of freedom for positioning and aligning a target at the laser beam focus (Fig. 1*a*–*c*). Therefore, HAMS has a hybrid kinematic structure, comprising parallel and serial mechanisms. A hybrid structure is usually designed to overcome the inherent limitations of serial and parallel mechanisms, such as low accuracy and limited workspace, respectively, while exploiting the advantageous characteristics of both types, namely large workspace and high accuracy [9,10]. An application, for example, requiring high-accuracy motion over a relatively large workspace can use a hybrid structure as an effective solution. Tricept and Exechon are examples of two commercially available hybrid machine tools [11,12]. Although hybrid structures have recently received much attention, and research is underway on how to use them in industrial applications, comprehensive studies of their design, kinematics, dynamics and error sources are lacking [12].

In addition to a tripod and a two-axis linear stage, HAMS has an interface wheel to which target sections, made using micro-electro-mechanical system (MEMS) techniques and typically from a silicon wafer, are attached, and a number of different target sizes/designs are patterned around the circumference of the section (see Fig. 1*c*–*e*). The ability of HAMS to provide positioning and alignment accuracy of the target within the defined specification is dependent upon a number of factors, such as the target geometry, accumulation of errors on the motion stages and the tripod (rotational and translational motion

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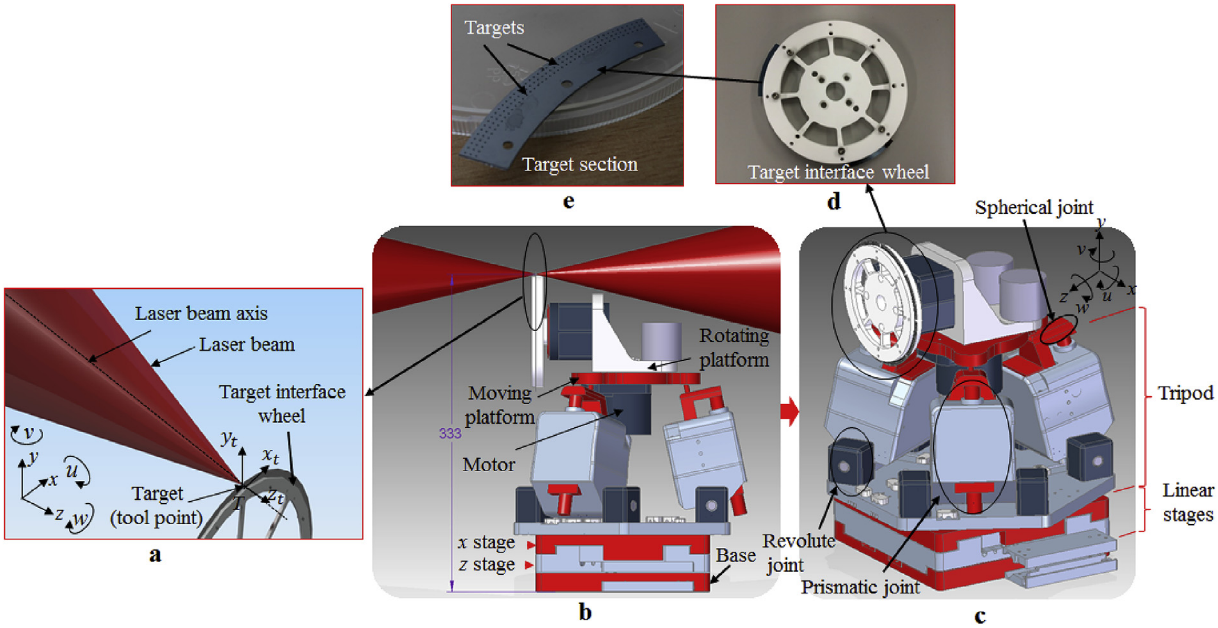

Fig. 1. HAMS for the high power high repetition rate laser operations: (a) laser beam-target interaction; (b) HAMS with the target interface wheel; (c) features of HAMS; (d) target interface wheel with two target sections; (e) targets patterned around the circumference of a target section (adapted from Refs. [4] and [8]).

errors, orthogonality errors, wobble/eccentricity errors, etc.), and the flatness tolerances on the wafer and interface wheel [6–8]. Many of these factors are examples of geometric errors, which can arise from the physical errors, such as manufacturing and assembling errors of the components of a mechanism, and joint errors of a mechanism. These geometric errors can affect the performance of a hybrid mechanism, just like any other precision machine and, therefore, error compensation is required to minimise the positional deviations at the target during the target alignment process [13,14]. Effective error compensation strategies for high-precision applications depend on identifying the sources of geometric error [15] and, as such, developing an error model based on kinematic analysis of the mechanism is essential for this purpose [15,16].

Developing an error model for a hybrid mechanism can be challenging for a number of reasons, particularly [17]:

- The error sources associated with serial kinematic mechanisms have been widely studied and are well understood [17–20], while those associated with parallel mechanisms are less well understood.
- Due to their relatively simpler kinematics, error analysis of serial mechanisms is mostly carried out following direct kinematic analysis, which determines a set of input joint variables to achieve a known pose (position and orientation) of the end-effector [12]. However, parallel mechanisms generally have more complex kinematics, and pursuing a direct kinematic analysis may be difficult.
- In all parallel mechanisms, various types of geometric error can be related to some physical errors, particularly machining and assembly errors of the mechanism, such as platform frame errors, pin joint errors and spherical joint assembly errors. Theoretical analysis to understand the effects of all these physical errors can be a complex and lengthy process. Although some studies have been pursued to understand the effects of the significant geometric errors of some parallel mechanisms [15,21], in most cases, the actual effects of the errors on the final position of the target remain unclear, since it is assumed that some error averaging effects take place for the parallel mechanisms as opposed to the cumulative addition of errors for the serial mechanisms.

In this paper, the development of a kinematic model for a particular type of hybrid mechanism HAMS is presented, with an analysis of the error sources and experimental validation to demonstrate how the errors may affect the positioning and orientation accuracy of targets during the CLF's target alignment process of the laser operations. Through the development of an error model for HAMS, this paper shows that a practical strategy to develop an error model for a hybrid mechanism should simplify the kinematic analysis of the mechanism. This is achieved by considering (a) the errors that may have significant effects on the particular motion/s of the mechanism, (b) the "generalised" errors, which can sufficiently describe the deviations of the geometric properties of a kinematic system in a mechanism, instead of considering all possible individual sources of geometric errors of that system, (c) the angular errors that can potentially be amplified by the structural offsets to produce significant translational errors at the target, and (d) the strategy of measuring the errors to estimate their effects on the positional accuracy of the target.

2. Motions of HAMS

In the HAMS hybrid mechanism, two translation motions (along x and z axes, see Fig. 1*b*–*c*) are generated from a linear xz system, which is a two degree of freedom (DOF) serial mechanism. The tripod, the parallel part of the hybrid mechanism, provides a rotational motion about the x axis (called tip u) and a translational motion along the y axis, while the rotary motor, which actuates the rotating platform mounted on the moving platform of the tripod, produces a further rotational motion about the y axis (called tilt v) (Fig. 1*a*–*c*). The moving platform of the tripod and the rotating platform can be considered as serially connected, jointly having three degrees of freedom. Since the linear xz system is widely used in industry and the technology is well developed, this research has focused on the error analysis of the parallel part (tripod) and its serially connected rotating platform. Note that an additional rotary motion (about the z axis) is required to rotate the target wheel, but this motion is not related to the tripod, rotating platform or linear xz system.

With regard to the 3 DOF platform (that is, moving and rotating as shown in Fig. 1*b*–*c*), only the tip and tilt motions are considered for the kinematic analysis of this paper. This is because tip and tilt motions control the orientation of the target on the target interface wheel. The