CALIBRATION AND ADJUSTMENT OF A HIGH-PRECISION FIVE DEGREE-OF-FREEDOM HYBRID MECHANISM

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INTRODUCTION

Positioning and aligning a target at the laser beam focal point to an accuracy of few micrometres represents a significant challenge for laser systems requiring positioning mechanisms with greater than and two degrees of freedom (DOF), and particularly hybrid mechanisms composed of both parallel and serial kinematic components [1]. To meet the accuracy, repeatability and speed requirements of high-power and high-repetition rate laser operations, the Central Laser Facility (CLF) has designed and developed a new high-accuracy microtargetry system (HAMS) for accurate mounting and motion control of targets for the Astra-Gemini laser [2,3]. Kinematically, HAMS uses a hybrid mechanism, in which a tripod (parallel mechanism) is serially connected to a two-axis linear system (serial mechanism), to control all five degrees of freedom (DOF) for positioning and aligning a target at the laser focus (see [3,4] for details). Targets are patterned around the circumference of the target sections, which are then attached to an interface wheel held on the moving platform of the tripod.

As with any other precision machine, a hybrid mechanism's performance can be affected by many sources of error. Thus, the accuracy of the final position of the target is influenced by the kinematic errors of the mechanism (usually the main sources) due to geometric errors, such as manufacturing and assembly errors of the joints, by load deformation due to external forces, and by thermal deformation [5]. These factors should be addressed with an appropriate error compensation method rather than changing the structure or design of the mechanism, which is often expensive. One method to compensate for geometric errors is to carry out kinematic calibration and adjustment (hereafter, just called calibration).

Kinematic calibration of a mechanism (serial or parallel) can be defined as a procedure to estimate the numerical values of the errors, which represent the differences between the actual and nominal values of the kinematic parameters, to better describe the kinematics of the mechanism, and these values are used to improve the mechanism's accuracy by acting on the mechanism's controller [6]. Generally, the calibration process has four steps: development of a model to relate the 3D Cartesian position of the end-effector (or target) to the kinematic parameters of the mechanism; acquisition of the actual end-effector positions and orientations using a measuring instrument; identification of the kinematic error parameters based on the model and measurement; and error compensation by adjusting the parameters of the controller [7].

Although it has been shown that kinematic calibration can be a practical and economical way for enhancing the accuracy of parallel mechanisms, the calibration process is more complex than for a serial mechanism [7,8]. This extra complexity is due to the significant difficulty in identifying the kinematic parameters using a minimum set of error data, which can be easily determined in a time- and cost-effective manner, without compromising the accuracy of the calibration results [7-9]. Although some general strategies for calibration based on minimum set of error data exist for serial mechanisms, for parallel mechanisms only calibration methods for individual mechanisms have been reported [6-11]. Finding general strategies for the cost-effective calibration is an important area of the current research in parallel mechanisms [7-11].

Furthermore, for hybrid mechanisms, despite recent research and considerable utilisation in industrial applications, comprehensive studies of their design, kinematics, error sources and calibration are lacking [12].

In this paper, a practical and cost-effective solution to the kinematic calibration of a hybrid mechanism is outlined to demonstrate the improvement of the accuracy of HAMS based on minimum set of error data.

KEY ISSUES IN CALIBRATING PARALLEL AND HYBRID MECHANISMS

Although the methodology for the calibration of serial, parallel and hybrid mechanisms follows the same procedure, a number of issues must be considered when developing a calibration process for a parallel or hybrid mechanism.

First of all, an effective model for a mechanism's calibration must describe all the possible sources of error. Moreover, each source of error should ideally be represented by one parameter only (no redundant parameters). Some researchers refer to such models as minimum complete and parametrically continuous (MCPC) [6,13]. There are mainly two approaches to develop a valid MCPC model, where [6,8]:

- Errors are described by the variations of a specific set of parameters used to define the mechanism's structure, such as link lengths, joint axes inclination and joint coordinates offsets. In terms of forward kinematics, the model can be represented as [14]
  $$S = f(Q, s_n + \Delta)$$
  where $S = [x, y, z, \alpha, \beta, \gamma]^T$ represents the end-effector's pose, $Q = [q_1, \dots q_n]^T$is the vector of the joint coordinates, $s = [s_1, \dots s_n]^T$ is the vector of the nominal structure parameters, and Δ is the vector of their errors. In many cases, these parameters are defined by adopting the well-known Denavit-Hartenberg approach [14].
- Errors are represented by a separate set of parameters describing the differences between the nominal and actual geometry of the mechanism. The forward kinematics of the model can be shown as
  $$S = f(Q, s_n, \Delta)$$
  where $\Delta = [e_1, e_2, e_3, \dots]$, which consists of geometrical error parameters.

Irrespective of which approach is used to develop a model for a calibration, since both have advantages and disadvantages, the number of parameters necessary to describe a parallel or hybrid mechanism (and, hence, their error parameters) can be very high. To give an idea from a literature survey, it is necessary to have up to 138 error parameters for a 6-DOF Stewart-Gough platform, a minimum of 38 parameters to describe a 5-DOF parallel mechanism and 33 parameters to describe the 3-DOF parallel mechanism of a 5-DOF hybrid machine tool [8,10,11]. This represents a significant challenge in the calibration process when developing a suitable representative kinematic model of the mechanism with a minimum number of error parameters.

Furthermore, adopting a suitable measurement scheme to identify the error parameters can be another challenge in calibrating a parallel or hybrid mechanism. Existing calibration methods are usually categorised as external calibration and internal or self-calibration [9,10]. External calibration, in which the geometric error parameters are identified by minimising the residuals between the end-effector's actual pose measured by an external measurement system (such as, laser tracker, camera, interferometer) and the predicted pose of the mechanism's controller, can be carried out by either full pose or partial pose measurements. Internal calibration, in which the identification is implemented by minimising the residuals between the actual values of the active and/or redundant joint sensors and the predicted joint values of the controller, is carried out only by partial pose measurements. Full pose measurements can be effective in identifying all possible error parameters required for the calibration; however, they can be difficult to achieve, requiring the measurement of a high number of poses for a parallel mechanism [9]. On the other hand, partial measurement can be cost- and time-effective, but only a partial set of error parameters are identifiable [10,11]. In some cases, a hybrid calibration method is used to reconcile the advantages of both methods.

This paper proposes a practical calibration method for a hybrid mechanism by taking into consideration the use of the mechanism for the target alignment operation of the CLF. As such, the calibration uses a simple model with a minimum number of error parameters which can be easily measured by selecting the poses relevant to the target alignment, and the compensations are then applied to the mechanism's controller with limited changes to its parameters.

CALIBRATION APPROACH FOR HAMS

For the convenience of the modelling, the structure of HAMS is briefly reviewed here, while the details can be found elsewhere [4]. HAMS has three sub-structures (see Figure 1). A linear *xz* system, producing two translation motions along *x* and *z* axes, forms sub-structure 1. Sub-structure 2 is the tripod, the parallel part of the hybrid mechanism, providing a rotational motion about the *x* axis (called tip *u*) and a translational motion along the *y* axis. Sub-structure 3 is essentially a rotary motor which actuates the rotating platform mounted on the moving platform, and produces a rotational motion about the *y* axis (called tilt *v*). The parallel structure is called an RPS mechanism, in which each chain is composed of a revolute joint (R), a prismatic join (P) and a spherical joint (S). To calibrate the hybrid mechanism, a step-by-step strategy was adopted in this study, which means the calibration procedure was carried out on the parallel part first. This was done because it was required to know the actual performance of each sub-structure independently for the purpose of the laser target alignment operation. In this paper, the calibration problem will focus on the RPS of the hybrid mechanism.

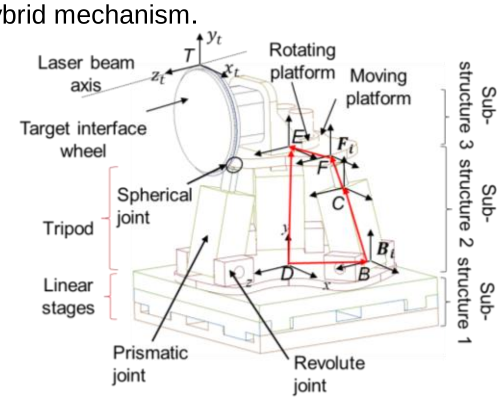

FIGURE 1. Kinematic structure of HAMS.

MODELLING

Figure 1 schematically represents the kinematic structure of HAMS, showing the geometrical relationships among the coordinate systems placed at the points of interest for the analysis, such as point *T*, which indicates the target position, and point *D* and *E*, which indicate the centroids of the fixed platform and the moving platform of the tripod. The origins of the coordinates are also placed at *B*, the centre of the rotational joint, at *C* on the prismatic joint, indicating the home position of the joint, and at *F*, the centre of the spherical joint. The three prismatic joints of the tripod's legs are driven to obtain the nominal pose $q = [\,y, u, v]^T$ of the moving platform through changing the distance ∇ between $\boldsymbol{B_i}$ and $\boldsymbol{F_i}$, where $\boldsymbol{B_i}$ is the position of point *B* with respect to the coordinate at *D*, $\boldsymbol{F_i}$ is position of *F* with respect to the coordinate at *E* and ∇ are the kinematic parameters. A revolute joint can be defined by four structural parameters (two positional and two rotational), since the position of the mechanical hinge is not relevant in its kinematic analysis but only the location (position and direction) of its geometrical axis [13]. For a prismatic joint, only the axis direction is relevant and thus two rotational parameters are enough. A spherical joint needs three parameters to be defined, since only the position of the sphere is relevant. Thus, for calibration purposes, each leg of the parallel mechanism needs 9 error parameters and, therefore, 27 error parameters for the whole mechanism.

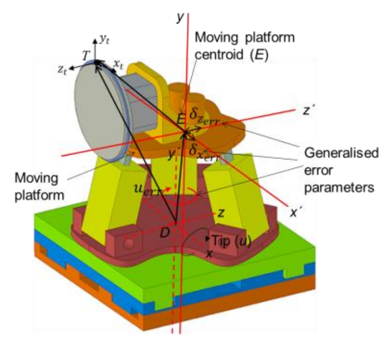

FIGURE 2. Kinematic model of HAMS.

The number of error parameters can be reduced to a minimum by carefully considering the kinematic constraints of the RPS mechanism. Each leg of the RPS is connected to the fixed base by a revolute joint at *F*, and the planes in which the spherical joints are allowed to move should ideally intersect at *E* [4]. In reality, during the rotations of the moving stage (tip *u* in this case), two translational parasitic motions (in the *x* and *z* directions) and one rotational parasitic motion about *y* are generated, which means that point *E* changes its positions in the *x* and *z* directions with respect to point *D* (these three error motions can be defined with a 4×4 matrix with respect to the coordinate at *E*). Since only the positions of the revolute joints are affected if there are kinematic errors generated from any source of a leg (revolute, prismatic or spherical joints), it is logical that the three parasitic motions of the moving platform actually contain the resultant effects of the errors stemming from the legs. These three errors, related to the tip rotation of the platform, are defined as the generalised error parameters of the tripod. Thus, the kinematic model can be redrawn as shown in Figure 2, in which all the coordinates between *D* and *T* (not all are shown) are placed in a serial manner. The details of the error model development are described elsewhere [4]. The equations used to describe the positional deviations of the target can be derived by writing the necessary transformation matrices for all the coordinates of the mechanism, with and without error conditions. The positional deviation equations of target *T* are in the following form:

$$D_{xt_{tip\,err}} = \delta_{x_{err}} - (d_3 + t_z)(\cos v \sin u_{err} + \sin v \cos u_{err})$$
$$+ t_x(\cos v \cos u_{err} - \sin v \sin u_{err} - 1), \qquad (1)$$

$$D_{yt_{tip\,err}} = (h_5 + h_6 + t_y)(\cos u - 1)$$
$$+ (d_3 + t_z)\sin u\,(\cos v \cos u_{err} - \sin v \sin u_{err})$$
$$+ t_x \sin u\,(\cos v \sin u_{err} + \sin v \cos u_{err}), \qquad (2)$$

$$D_{zt_{tip\,err}} = \delta_{z_{err}} - (h_5 + h_6 + t_y)\sin u$$
$$+ (d_3 + t_z)(\cos u \cos v \cos u_{err} - \cos u \sin v \sin u_{err} - 1)$$
$$+ t_x \cos u\,(\cos v \sin u_{err} + \sin v \cos u_{err}). \qquad (3)$$

where, *u* and *v* are the tip and tilt motions; $\delta_{x_{err}}$, $\delta_{z_{err}}$ and u_{err} are the generalised error parameters; h_5, h_6, d_3, t_x, t_y and t_z represent the structural offsets of HAMS.

MEASUREMENTS AND ERROR IDENTIFICATION

The following should be noted.

1. The inverse kinematics in the hybrid system's controller are capable of compensating the motions in the *x* and *z* directions; however, these compensations are based on an inverse kinematic calculation of the controller, may not necessarily be accurate, and, therefore, need to be evaluated in the calibration.

2. Equations (1) to (3) show that four sources are responsible for the positional deviations of the target:

- tip motion, since the target is at an offset in the *x* and *y* directions from the centroid of the moving platform (Abbe offsets),
- structural parameters between the centroid of the platform and the target,
- positional deviations at the centroid of the platform that include the parasitic motions $\delta_{z_{err}}$ and $\delta_{x_{err}}$,
- the rotational parasitic motion u_{err} causing Abbe errors at the target due to the offsets.

The measurement process of the calibration, shown in Figure 3, is explained below.

i. RPS is a 3-DOF mechanism; therefore, if the tip (*u*), tilt (*v*) and *y* (height) values of the platform are specified, the other three parameters ($\delta_{z_{err}}$, $\delta_{x_{err}}$ and u_{err}) can be determined. Because, orientation of a target is adjusted once the target is placed at a certain position (according to the CLF's target alignment process), and also because the tilt (*v*) of the moving platform is not used, only the tip motions of the platform were considered in the calibration process (therefore, *v* = 0 and *y* is fixed). The tip motions were selected such that they are representative of the range of rotational motions normally used in the CLF's target alignment procedure.

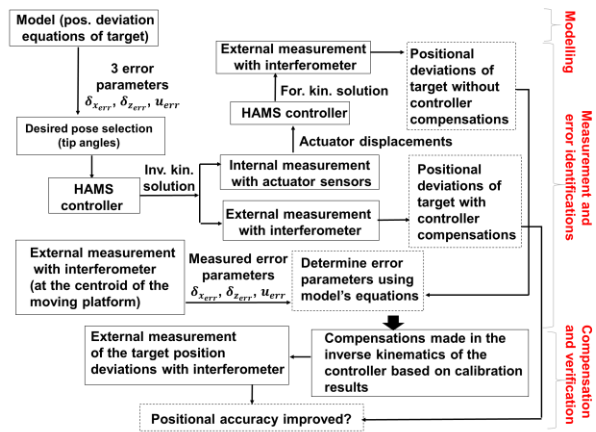

FIGURE 3. The calibration process flow diagram of HAMS.

ii. Once the desired tip angles were entered into the controller, the displacements of the target were measured using a displacement interferometer (Renishaw XL-80). The *z* motions were determined from the *z* stage actuator sensor (no *x* displacement observed), meaning that the *z* positional deviation values from the interferometer reading included controller compensation.

iii. Displacements of the three actuators of the tripod, as determined from the sensors for the particular tip motions, were used as the forward kinematics input of the controller. The target's tip angles and positional deviations were measured with the interferometer. It was found that *z* displacements varied from those measured in step ii. No *x* or *z* stage sensor motions were determined in this case, meaning no controller compensation is included in the measured positional deviations, which represent the actual positional deviations during the tip motions of HAMS.

iv. The positional deviations of the target from step iii could be used in the model equations (1) to (3) to find the error parameters $\delta_{z_{err}}$, $\delta_{x_{err}}$ and u_{err} (for known structural parameters). Alternatively, these were measured directly at the centroid of the moving platform of the tripod using the interferometer (the details are given elsewhere [4]). When using these parameter values in the model equations, the predicted positional deviations agreed with the values measured in step iii.

COMPENSATION AND VERIFICAITON

It was found that the controller compensated for the $\delta_{z_{err}}$ error motion in the *z* direction; however, the relatively smaller error motion $\delta_{x_{err}}$ in the *x* direction remained uncompensated. For small angle rotations, the measured values of $\delta_{z_{err}}$ and $\delta_{x_{err}}$ are found to vary linearly with the tip angles (see [4] for details) and, therefore, it was possible to compensate for these deviations as functions of tip rotations in the inverse kinematic solution of the controller. Alternatively, the values of the target positional deviations were included in the inverse kinematics to generate compensations in the *x* and *z* directions as functions of tip rotations. After compensations, the interferometer was used to measure the positional deviations of the target for various tip rotations. The results were compared with the positional deviations measured in step ii to verify the improvement achieved through this calibration process.

CALIBRATION UNCERTANITIY

The overall measurement uncertainty arising from the repeatability of the measured distances and from the atmospheric effects on the interferometric measurements was estimated to not to exceed 180 nm (at a coverage factor k = 2, giving a confidence level of approximately 95%). The values of measurement uncertainty, compared to the positional deviations measured on the micrometre scale, are not shown in the calibration results as they are relatively small.

However, there are a number of influence factors in this calibration that need to be further investigated, for example:

- since the *xz* platform makes *xz* motions for compensations, the stages' accuracy should be considered as an influence factor when measuring the target's position deviations;
- the nominal values of the structural offsets between the centroid of the platform and the target were used; also, the perpendicular errors between any two structural features were ignored;
- the measurements to determine the error values $\delta_{z_{err}}$, $\delta_{x_{err}}$ and u_{err} were taken as close to the centroid of the platform as possible, instead of at the centroid.

RESULTS AND DISCUSSION

The key points of the calibration results are as follows.

1. The controller's compensations for the *x* and *z* positional deviations during tip rotations were evaluated (Figure 4). While the controller is overcompensating for the positional deviation in *z*, there is no compensation in the *x* direction. Although the *z* direction accuracy is the most sensitive to the target alignment, the *x* and *y* direction accuracies are also important; otherwise, the laser will miss the targets.

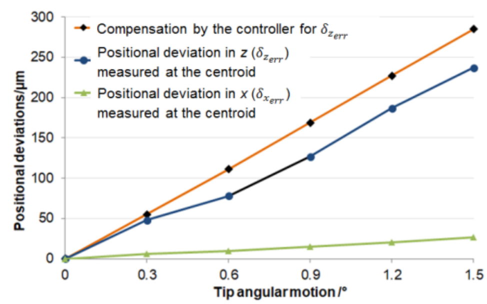

FIGURE 4. Comparison between the actual positional deviations at the centroid of the platform and the compensated values by the controller.

2. The positional deviations of the target predicted by the error model agree with those measured (uncompensated values before calibration) - see Figure 5. This shows the validity of using a simplified kinematic model with generalised error parameters in the calibration of this 5-DOF hybrid mechanism.

3. Figure 6 shows that the position accuracy of the target has improved significantly (more than 85%) in the *x* and *z* directions. However, the calibration of the complete hybrid mechanism will be part of our on-going research.

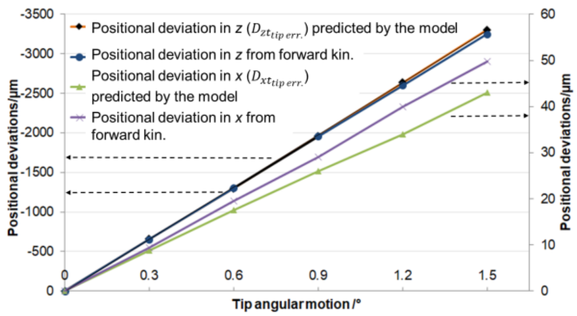

FIGURE 5. Comparison between the target positional deviations predicted by the model and the measured values.

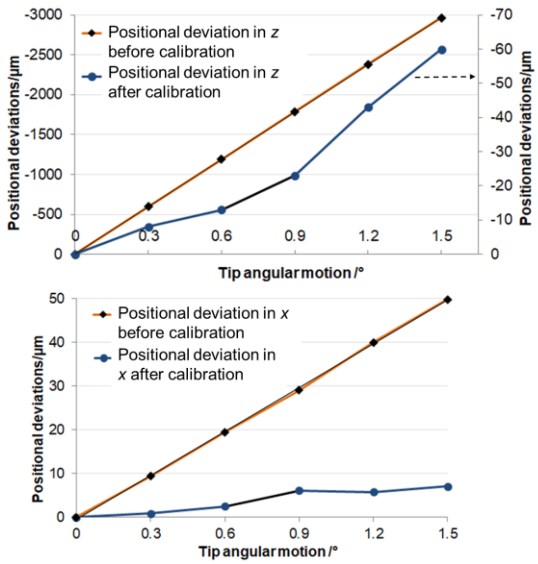

FIGURE 6. Target position accuracy improvement through the calibration process.

CONCLUSION

Calibration of a parallel or hybrid mechanism is a difficult problem in terms of developing a suitable kinematic model, identifying error parameters, adopting cost-effective measurement plans and implementing compensations into the mechanism's controller. This problem is approached in this study in a practical way with the help of a simplified model with minimum error parameters, by carrying out simple measurements and by compensating the errors using effective steps, resulting in a significant improvement in the target positioning accuracy. Future work involves the development of a closed-loop control system for HAMS for automatic alignment of the targets to the laser focus with high-repetition rate.

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