Metrology system for the calibration of multi-dof precision mechanisms

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ABSTRACT

We have developed a novel metrology system for precision XY measurements based on a concept developed originally in an industrial vision context by which USB cameras observe a target with a special dots pattern. The system has then been extended to Rx-Ry (tip-tilt), Z and Rz measurements by adding more cameras within a suitable configuration. The basic principle is described, first validated on a preliminary experimental implementation used for testing a new type of hexapod. We then illustrate the setup designed as calibration bench for hexapods used as positioning devices of the secondary mirrors of astronomical telescopes. While work is still ongoing for improving this new metrology system, currently achieved performances are a stability of is \( \leq 1 \) \( \mu \)m along linear degrees of freedom, respectively 0.5 arcsec for tip-tilt; absolute accuracy over ranges of a few millimeters is 5-10 \( \mu \)m, respectively arcsec; incremental accuracy is 2-3 \( \mu \)m, respectively 5 arcsec.

Keywords: multi-degree-of-freedom metrology; hexapod, calibration.

1. INTRODUCTION

Like many modern advanced instruments, astronomical telescopes employ high-precision mechanisms for adjusting and aligning optical elements. In many instances such stringent alignment must be done concurrently in multiple degrees of freedom (dof). Hexapods and similar 6-dof parallel manipulators are often used.

A typical example are hexapods used as alignment devices for the secondary mirror of telescopes, which must be accurately positioned and generally also continuously adjusted (albeit slowly) along 5 degrees of freedom: \( x,y,z,RxRy \) (\( z \) being here the telescope sight axis).

Figure 1. Secondary mirror of the VLTI auxiliary telescopes at the ESO Paranal Observatory with its hexapod-alignment mechanism.

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The accuracy performance of the VLTI hexapods is resumed in table 1 below.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Focus ((z)) range</td>
<td>(\pm 1.5) mm</td>
</tr>
<tr>
<td>Focus resolution</td>
<td>(\leq 1\ \mu)m</td>
</tr>
<tr>
<td>Focus accuracy</td>
<td>(\leq 6\ \mu)m</td>
</tr>
<tr>
<td>Center ((x,y)) range</td>
<td>(\pm 0.7) mm</td>
</tr>
<tr>
<td>Center resolution</td>
<td>(\leq 5\ \mu)m</td>
</tr>
<tr>
<td>Center accuracy</td>
<td>(\leq 20\ \mu)m</td>
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<tr>
<td>Tip-tilt range</td>
<td>(\pm 300\ \text{arcsec})</td>
</tr>
<tr>
<td>Tip-tilt resolution</td>
<td>(\leq 5\ \text{arcsec})</td>
</tr>
<tr>
<td>Tip-tilt accuracy</td>
<td>(\leq 20\ \text{arcsec})</td>
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Table 1. Nominal performance of the VLTI hexapods.

The metrology system required to evaluate and calibrate the hexapods shall be capable of better resolution and accuracy than the performance intrinsically required by the tested mechanism, at least by some significant factor. Figure 4 below illustrates the optical metrology system used originally at CSEM as the calibration and test bench of these hexapods.

While this kind of optical instruments will likely still remain for some time the most accurate, recent years have seen a very strong development of innovative industrial vision applications. These make use of digital cameras and process target information according to specific industrial needs. Some applications also concern accurate position or displacement measurements, often in industrial environments and applications which are not favorable to the traditional optical instruments.

![Figure 2](image)

Figure 2  The 5 degrees of freedom of the hexapod were measured by an autocollimator, a rectitude sensor (actually a modified autocollimator operated with a corner cube) and an interferometer.

There is therefore a drive to develop innovative methods which make use of digital cameras and essentially implement in software the information processing leading to high precision position displacement measurements. The application and adaptation of such novel methods also to measurements of advanced opto-mechanisms for astronomy becomes interesting, particularly since the cost of the measurement instruments is vastly reduced with respect to current precision interferometers and autocollimators.
2. PRINCIPLE

2.1 Position measurement on a plane

The principle of the metrology system was initially developed to monitor the linear position of a target moving on a plane – defined by its x and y axes.

In order to evaluate the position in a plane the system needs a Cartesian reference suitably coded. We use here a reference pattern coded with four types of circular shapes (dots):

Each dot is coded with two bits which represent the x and the y coordinate, and are respectively associated to the center and the ring sections. The dots can be efficiently decoded from their level of grey.

The target pattern is then generated with a MLS 8-bit code, whereby all lines and respectively all columns have the same bit sequence. Different coding sequences are used for the x and y axes. The step between the dots represents the measurement scale. The typical target grid pattern will have several tens dots per side:
Any subsection of at least 8x8 dots will have a unique location on the grid. Hence its absolute position can be computed on the grid. However this will be only a rough positioning, i.e. some fraction of the grid resolution (which is typically 1-2 mm). Fine positioning is computed by Fourier analysis of the 8x8 subsection. The grey values of all pixels of each row are summed, which provide a function of the type illustrated below in figure 6 (curve above). This function is then approximated by a Fourier series of first order (curve below). The phase of the signal will then provide the sought fine position information.

Figure 4. A row coding sequence and its Fourier first order approximation

The method described above allows measuring concurrently the x and y coordinates of a moving target. A practical demonstration setup of such measurement is illustrated here below.

Figure 5. 2-dof demonstration metrology system

The measurand with the target pattern is mounted on two precision linear guides and is observed by an industrial USB camera. Processing is done with a standard PC.

2.2 Extension to multi-dof measurements

Adding a further measurement axis, i.e. z, requires another camera and a suitably located target pattern on the measurand, perpendicular to the one providing the x-y measurements.

The method can be extended as well to the measurement of rotation degrees of freedom. However in this case the target pattern is attached to the fixed reference and is observed through a plane mirror on the measurand. When the mirror is tilted, the camera will actually see a shift of the pattern, which then can be processed with the same method.

For instance, with reference to figure 5, if $d$ is the distance between the flat mirror and the fixed target, when the camera sees an apparent motion of the pattern by a length $x$, the tilt angle $\beta$ of the mirror about the y axis is

$$\beta = \frac{1}{2} \arctan \left( \frac{x}{d} \right)$$
In the schematic illustrated in the next figure three cameras are used to measure the six degrees of freedom of the mobile part actuated by a hexapod type mechanism.

For simple motions, i.e. no cross-coupling, camera 1 measures the \(x\)-\(y\) coordinates, camera 2 takes care of the \(z\) coordinate (as well as \(y\) redundantly), camera 3 measures the tip-tilt motion \(Rx-Ry\). This application does not require the \(Rz\) measurement, which however could readily be obtained from combining results from cameras 1 and 2, as the latter observes an off-axis target.

Yet because of the setup geometry, when motions are combined the six measurements of the cameras do not provide directly the \(x,y,z,Rx,Ry,Rz\) coordinates of the hexapod. These can be obtained, however, by transformations analog to the method used in computing inverse and forward kinematics of a parallel mechanism.

The analog of an inverse kinematic calculation is used to compute the six displacements \(\Delta D_i\) observed by the cameras for a given motion of the measurand:

\[
\Delta D_i = f(\Delta x \Delta y \Delta z \,Rx \,Ry \,Rz)
\]

Let us define the desired displacement of the mobile part \(u = (\Delta x \Delta y \Delta z \,Rx \,Ry \,Rz)\) with respect to a zero position in terms of the homogenous transformation matrix \(R\) (4x4) relative to the system references axes. The homogenous transformation method and the computation of the matrix are described in several books on robotics and serial links in particular. Let us set the matrix \(PM\) (6x3) with the coordinates \((x,y,z)\) of the two mobile targets (observed by cameras 1 and 2) and the mirror (through which the displacement observed by camera 3 is effected).

Consider the item \(i\) and define the vector \(PM_i\) where the first 3 terms of \(PM_i\) are the \(x,y,z\) coordinates of the target, respectively mirror and the fourth term is 1:

\[
PM_i = \begin{bmatrix}
PM_{i,1} \\
PM_{i,2} \\
PM_{i,3} \\
1
\end{bmatrix}
\]
The positions of the targets, respectively mirror after the displacement are computed as:

$$\text{PM}_{i_{\text{new}}} = R \times \text{PM}_i$$

where the first 3 terms of $\text{PM}_{i_{\text{new}}}$ are the x,y,z coordinates of the targets, respectively mirror.

By setting very small displacements, $u = (\Delta x \ \Delta y \ \Delta z \ \Delta Rx \ \Delta Ry \ \Delta Rz)$ one degree of freedom at the time, one can obtain a linear transformation matrix $T$ with which actuator displacements can be estimated as:

$$\Delta D_i = u \times T$$

The matrix $T$ can be inverted and hence a linear approximation to the forward kinematics can be obtained by:

$$u = \Delta D_i \times T^{-1}$$

### 3. DESIGN OF A PROTOTYPE SETUP

In initial proof-of-concept demonstration was done in collaboration with NIAOT (Nanjing Institute for Astronomical Optics and Technology) and is reported in ref. [2].

The next phase of the project consisted in producing a test bench for the hexapods used in the 1.8-m interferometric telescopes of the ESO Paranal Observatory for the alignment of the secondary mirrors.

Whenever the hexapods are dismounted for maintenance it would be desirable to recalibrate the actuated displacements. Calibration along five degrees of freedom is here required (x,y,z,Rx,Ry) as rotation about the z axis of the telescope does not have optical effects.

The test bench (figure 7) is essentially a stiff disk-shaped plate on which the hexapod is attached. The disk can be rotated in order to verify the hexapod calibration under different gravity vectors. Three industrial USB cameras are used according to the schematic of figure 6 above.

Calibration and validation with respect to all six degrees of freedom was performed with a 6-dof mechanism constituted of a piling-up of micrometric tables. While the micrometric tables already provide micron accuracy for the linear degrees of freedom, accurate setting of the tip-tilt angles was provided by high-precision inclinometers (figure 8).

![Figure 7](image_url)  
Figure 7. Left: general design of the test bench for the VLTI hexapods. Right: the latest test bench prototype: here the “hexapod” is represented by a piling-up of micrometric position tables allowing the mobile plate to be displaced along all 6 degrees of freedom.
Proper illumination of the target patterns is a key aspect for optimum performance. AC-supplied light sources such as incandescent lamps or even neon lights will add significant noise to the image signals, but white LED lights appear to provide optimal illumination.

The current solution consists of LED backlight illuminated target panels, which provide a good homogeneity and constancy of illumination level. The intensity of lighting is set by a PWM with given duty cycle.

4. MEASUREMENTS AND VALIDATION

As work is ongoing and the system quality is still some way from its achievable limit, we present here some preliminary relative to linear and tip-tilt measurements.

Figure 8 As control instruments we have used high-precision inclinometers (0.01 mrad) to provide control measurements for the tip-tilt angles, while a Heidenhain length gauge (1 µm nominal resolution) is used for control of linear displacements.

4.1 Stability

Figure 9 Stability measurements for linear focus, decenter and tip-tilt over a time period of 30 minutes. The standard deviation is a fraction of respectively 1 micron and 1 arcsec.
4.2 Absolute accuracy

Note that the absolute accuracy performance is less critical for this type of positioning hexapod than the resolution, i.e. the smallest displacement effectively achievable. Nonetheless a good absolute accuracy performance is an indicator of overall good quality for any precision system. The next figures show typical results obtained. Note that these results actually integrate not only the measurement errors from the metrology system but also the inherent uncertainties of the pile of micrometric tables and of the control instruments.

Figure 10 Absolute accuracy of X-linear measurements. Here the gross error was less than 2.5 µm in standard deviation.

Figure 11 Absolute accuracy of Rx tilt measurements. Here the gross error was less than 4 arcsec in standard deviation.

4.3 Incremental accuracy and resolution

Precision optomechanical systems such as the VLTI hexapods are in most cases used to provide small incremental adjustments, commanded in closed loop with feedback from the instrument sensors. Therefore resolution and incremental accuracy, i.e. the capability of performing very small adjustment steps is the key performance to be achieved and verified.
Figure 12  Resolution of decenter ($x,y$), focus ($z$) and tip-tilt ($Rx,Ry$) measurements. Steps of a 2-3 microns, respectively 5 arcsec are easily and exactly measurable.
5. CONCLUSIONS

We are developing a novel 6-degrees-of-freedom metrology system for high-precision optomechanical positioning devices such as hexapods used in telescopes. The system is based on industrial vision technology and makes use of USB cameras.

Work is still ongoing: while the performance of this novel metrology system will likely remain inferior to that of interferometers and autocollimators, it will be very adequate to measure the performance of most high-precision optomechanisms used in astronomical telescopes.

The advantages of the system will be a cost which is considerably lower, as well as an inherent robustness to environmental conditions much better than with more delicate instruments such as interferometers and autocollimators.

6. ACKNOWLEDGMENTS

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REFERENCES
