Precision absolute measurement and alignment of laser beam direction and position

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For the construction of high-precision optical assemblies, direction and position measurement and control of the involved laser beams are essential. While optical components such as beamsplitters and mirrors can be positioned and oriented accurately using coordinate measuring machines (CMMs), the position and direction control of laser beams is a much more intriguing task since the beams cannot be physically contacted. We present an easy-to-implement method to both align and measure the direction and position of a laser beam using a CMM in conjunction with a position-sensitive quadrant photodiode. By comparing our results to calibrated angular and positional measurements we can conclude that with the proposed method, a laser beam can be both measured and aligned to the desired direction and position with 10 μrad angular and 3 μm positional accuracy.

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1. Introduction

In various science fields, the demand for high-precision, complex, compact, and robust optical assemblies is increasing [1–8]. In particular, applications in space set tight constraints on the envelope, stability, and endurance of optical assemblies that can only be met with specialized permanent manufacturing techniques such as hydroxide-catalysis bonding [9–12].

During the manufacturing process of optical assemblies, the position and orientation of the optical components is often controlled using coordinate measuring machines (CMMs, [13]). However, not only do the optical components need to be aligned to specified positions and directions, but also the laser beams that are routed through the assembly. This is much more demanding than the alignment of the optical components, since the beams cannot be physically contacted.

One possible solution to align a beam to a desired position and direction is to install two small apertures through which the beam can only pass if it is properly aligned. However, this method gives very limited accuracy.

A more elaborate approach is to use a calibrated quadrant photodiode pair (CQP, [14]): two position-sensitive quadrant photodiodes (QPDs) are installed in a mechanically stable housing. The device is calibrated in a way that a beam entering the CQP and centered on both QPDs has a known offset and direction with respect to the housing. Care has to be taken that the housing is stable enough so that the calibration remains valid throughout the measurement process. Also, a four-axes rotation/translation stage is required to align the CQP to the beam axis.

We present a novel method to both align and measure the beam direction and position using a CMM and a single position-sensitive QPD. We call our

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method CMM-assisted beam alignment and measurement (CABAM). CABAM is easy to implement, since only one QPD on a simple two-axes translation stage is needed. No stable housing and no calibration are required.

We have tested CABAM against calibrated CMM positional and autocollimator angular measurements to validate the obtainable accuracies.

2. CABAM Measurement Method

CABAM is a novel method to both align and measure the laser beam direction and position using a CMM and a position-sensitive QPD. The basic concept is to measure 3D points $\vec{p}_i$, $i = 1, \ldots, n$, along the laser beam and fit a 3D ray $\vec{b}(s)$ to these points:

$$\vec{b}(s) = \vec{p}_0 + s \cdot \vec{w}. \tag{1}$$

We choose as a support point for the ray

$$\vec{p}_0 = \frac{1}{n} \sum_{i=1}^{n} \vec{p}_i, \tag{2}$$

while the direction vector $\vec{w}$ of the ray can be determined with a least squares fit using, e.g., singular value decomposition [15].

The position and orientation of the beam are fully characterized by the ray support point $\vec{p}_0$ and by the ray direction vector $\vec{w}$. Furthermore, the deviation of the measured points from the fitted ray allows us to estimate the achievable positional precision and, via the lever of the distance over which the measurement points are distributed, also the angular precision.

The crucial step in our method is to measure 3D point positions along the beam. This is accomplished by use of a CMM in conjunction with a position-sensitive QPD.

Usually, the CMM measures a point position on a test object by approaching the object and physically touching it with its probe sphere, which is located at the end of the CMM probe head shaft. When a calibrated force is applied to the shaft, the respective position that is being touched on the object under test is recorded.

Unfortunately, we cannot “touch” a laser beam with the CMM probe sphere. Yet even when the CMM probe sphere is not in physical contact with an object, the position of the center of the probe sphere is still provided by the CMM software. The positional accuracy of this noncontact mode is not calibrated and will have to be compared to the calibrated contact positional accuracy of the CMM.

Now we need a means to center the CMM probe sphere in the beam correctly. This will immediately give us a measurement point $\vec{p}_i$ on the beam axis.

The alignment procedure of the CMM probe sphere is described in Fig. 1: (1) first, we center a position-sensitive QPD on a two-axes translation stage in the beam. (2) Second, we make use of the fact that the CMM probe sphere is usually a sapphire ball that is transmissive for the laser beam and has the same effect as a ball lens. We position the sapphire ball of the CMM probe head in the beam such that the beam remains centered on the QPD. This is only the case when the beam passes through the center of the sapphire ball.

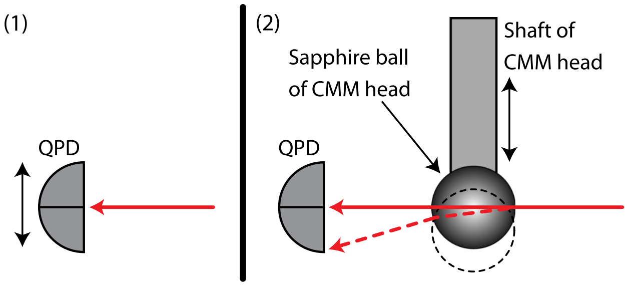

Fig. 1. (1) First, the incoming beam (arrow from right) is centered on a position-sensitive quadrant photodiode (QPD) by moving the QPD on a translation stage in two dimensions transversal to the incident beam. (2) Second, the sapphire ball of the CMM probe head is positioned in the beam such that the beam passing through the sapphire ball remains centered on the QPD. The dashed arrow line indicates the beam path when the CMM sapphire ball is not positioned correctly (dashed ball) in the beam, leading to a nonzero beam-displacement signal from the QPD.

Once the CMM probe sphere has been positioned correctly such that the beam-displacement-sensitive signal of the QPD is minimized, the position of the probe sphere and thus a point $\vec{p}_i$ on the beam axis can be read out from the CMM software. After measuring two or more points, the corresponding ray [Eq. (1)] can be reconstructed.

3. Measurement Setup

We now want to demonstrate the feasibility of CABAM and investigate the achievable accuracies. We do this by testing CABAM against calibrated angular and positional measurement devices.

We have tested the *angular accuracy* of CABAM against an autocollimator (AC), which monitors the tilts of a steering mirror over which the measured beam is guided.

To confirm the *positional accuracy* of CABAM, we have used a CMM in calibrated contact mode by inserting a separate ball lens into the beam and measuring its position.

We present the measurement setup in Fig. 2. A beam generated by a Mephisto 500 laser (Innolight GmbH) at 1064 nm is delivered via an optical fiber to the fiber collimator (SUK60FC-4-A11-03, Schäfter&Kirchhoff GmbH), which produces a collimated beam with 1 mm waist diameter.

The beam is guided over the mirrors M1 and M2. Mirror M2 is monitored with an autocollimator (ELCOMAT direct SN-162, Möller Wedel, calibrated angular accuracy ±0.34 μrad). The autocollimator axes are aligned to the horizontal plane of the CMM coordinate system to better than 1°. This has been confirmed by tilting mirror M2 both horizontally and vertically and comparing autocollimator

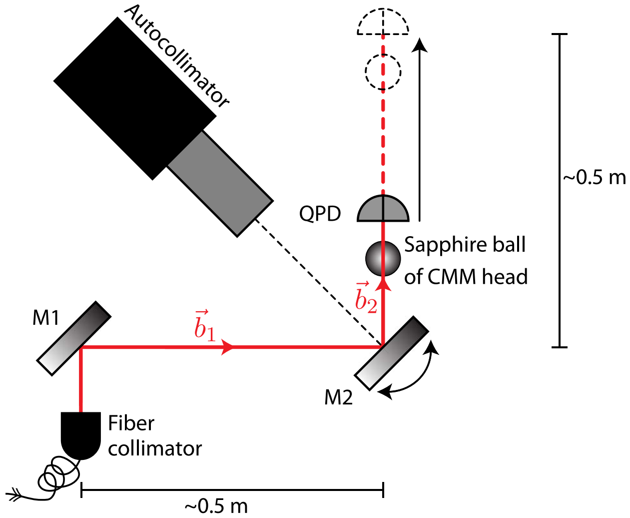

Fig. 2. In this setup, we compare CABAM beam orientation measurements with calibrated autocollimator angular measurements. First, we measure the position and orientation of the laser beam before ($\vec{b}_1$) and behind mirror M2 ($\vec{b}_2$) with CABAM. Then we tilt mirror M2, record the tilt angle with an autocollimator, and repeat the orientation measurement of beam $\vec{b}_2$ using CABAM.

measurements with mirror M2 orientations obtained from CMM measurements of the M2 plane.

A position-sensitive QPD (silicon, 1 cm diameter, in-house electronics) on a two-axes translation stage can be inserted into the beam at various positions before and after M2 to measure points along beams $\vec{b}_1$ and b_2. There is enough space on the CMM table to move the QPD for 0.5 m along both beams $\vec{b}_1$ and $\vec{b}_2$.

The photocurrents produced by a laser beam incident on the four QPD segments are converted to voltages V_i, $i = A, B, C, D$, using a transimpedance amplifier (QPD segment naming convention: top left, A; top right, B; bottom left, C; bottom right, D). The voltages can be directly related to horizontal and vertical beam displacements Δx and Δy, respectively, from the QPD center:

$$\begin{aligned} \Delta x &= C \cdot \frac{V_A + V_C - V_B - V_D}{\sum_i V_i}, \\ \Delta y &= C \cdot \frac{V_A + V_B - V_C - V_D}{\sum_i V_i}. \end{aligned} \tag{3}$$

The calibration factor C is determined by inserting the QPD into the beam and then transversally moving it by a known distance.

The setup in Fig. 2 is installed on the table of a CMM (Global Advantage, GLOA 000670, probe head: Tesa-Star m, 3P005901, Hexagon Metrology GmbH, positional accuracy in calibrated contact mode better than ±2 μm over the whole measurement volume). We use a CMM probe head with a 50 mm long shaft and a 5 mm diameter sapphire ball in vertical orientation. Sapphire balls are commonly fabricated with a very high roundness and a deviation from the spherical shape of below 1 μm, so that distortions of the transmitted laser beam are negligible.

To compare the CABAM angular measurements with the autocollimator measurements, we first measure the orientation of the laser beam $\vec{b}_2$ with CABAM. Then we tilt mirror M2 and record the tilt angle with the autocollimator. Consecutively, the new orientation of beam $\vec{b}_2$ is measured with CABAM.

To compare the CMM probe sphere position in noncontact mode, which we need for CABAM, with the CMM probe sphere position in calibrated contact mode, we position a 9.525 mm diameter sapphire ball lens (63-227, Edmund Optics) on a two-axes translation stage in the beam $\vec{b}_2$ in the very same way as described in Section 2 for the CMM probe sphere. The position of the ball lens can then be measured with the CMM in calibrated contact mode and compared to the nominal beam $\vec{b}_2$ position, which is derived from CMM noncontact mode CABAM measurements.

In addition, we have demonstrated with the setup in Fig. 2 that CABAM can be used not only to *measure* the position and direction of a beam, but also to *align* a beam to a desired position and direction.

To accomplish this, we first set two points $\vec{q}_1$, $\vec{q}_2$ in the CMM software defining a ray

$$\vec{B}(s) = \vec{q}_1 + s \cdot (\vec{q}_2 - \vec{q}_1), \tag{4}$$

to which we would like to align beam $\vec{b}_2$. The points $\vec{q}_1$, $\vec{q}_2$ are about 0.5 m apart.

We now coarsely align beam $\vec{b}_2$ to the points $\vec{q}_1$, $\vec{q}_2$ by adjusting the near- and far-field beam positions iteratively with mirrors M1 and M2, respectively, and using the CMM probe sphere as a beam target at $\vec{q}_1$, $\vec{q}_2$.

After coarse alignment, we measure a point $\vec{p}_2$ on beam $\vec{b}_2$ in the vicinity of $\vec{q}_2$ using CABAM. After the measurement, we move the CMM probe sphere out of the beam so that the beam illuminates the QPD directly. With Eq. (3), the difference $(\vec{q}_2 - \vec{p}_2)$ can now be used to correct the beam position on the QPD with mirror M2.

We then repeat the procedure for the near field measuring a point $\vec{p}_1$ on the beam $\vec{b}_2$ close to $\vec{q}_1$ and correcting the beam position with mirror M1.

The alignment procedure converges quite quickly, so that usually three iterations with a total duration of 10–15 min are sufficient. Afterwards, the successful beam alignment can be verified with CABAM.

Since our proposed beam alignment method requires CMM measurements at multiple locations, it is nonimmediate. Thus for some active alignment applications, the CQP method [14] as mentioned in Section 1 or a combination of both methods might be more applicable.

4. Results

We have measured the beam direction and position for beams $\vec{b}_1$ and $\vec{b}_2$ in the setup shown in Fig. 1 by measuring points along the beams with CABAM as described in Section 2. The placement sensitivity of the CMM probe sphere in the laser beam was very high, with a 1 µm displacement from the beam center leading to a well-resolvable displacement signal from the QPD with a signal-to-noise ratio of 2.5. The noisefloor of the displacement signal from the QPD was dominated by beam jitter introduced by the fiber collimator.

Each beam measurement consists of three point measurements along the beam to which a ray is fitted according to Eq. (1). A three-point beam measurement takes about 10 min. For all measurements, the fit residuals were below 1 µm corresponding to an angular precision of $1\ \mu\text{m}/0.5\ \text{m} = 2\ \mu\text{rad}$. The fitted beams $\vec{b}_1$ and $\vec{b}_2$ were intersecting within less than 2 µm. For better statistics, a beam measurement with six points along the beam was performed. The root-mean-square distance of the points from the fitted ray was well below 1 µm, with the maximum distance being below 1 µm as well.

To confirm the *positional accuracy* of the beam measurement, we have aligned a ball lens on a two-axes translation stage at several locations in the beam $\vec{b}_2$ in the same way as described in Section 2 for the CMM probe sphere. For each location, we have measured the ball lens position by probing it with a CMM with 13 points. The measured ball lens positions deviated from the fitted $\vec{b}_2$ ray by less than 3 µm, which is close to the CMM measurement accuracy of 2 µm.

To confirm the *angular accuracy* of the beam measurement, we have measured beam $\vec{b}_2$ for five different orientations of mirror M2, which was monitored with an autocollimator. We have covered an angular range of $\phi_{\text{hor,vert}} \approx 300$ µrad in both the horizontal and vertical directions.

Since the beam direction and autocollimator axes are not linked in an absolute sense, we will only consider angular differences $\Delta\phi_{\text{hor,vert}}$ between the five investigated mirror orientations.

One also has to consider that a beam hitting a mirror at 45° incidence will be deflected by twice the angle if the mirror is tilted in the plane of incidence and by $\sqrt{2}$ times the angle for mirror tilts perpendicular to the plane of incidence. In the following, the autocollimator angles have already been corrected for these geometrical factors.

The angular difference measurements of the autocollimator $\Delta\phi^{\text{AC}}_{\text{hor,vert}}$ and of beam $\vec{b}_2$ direction $\Delta\phi^{b_2}_{\text{hor,vert}}$ as measured with CABAM for the different mirror M2 orientations are shown in Table 1.

Table 1. Comparison of Autocollimator-Measured M2 Mirror Orientation Differences $\Delta\phi^{AC}_{\text{hor,vert}}$ and $\vec{b}_2$ Beam Direction Differences $\Delta\phi^{b_2}_{\text{hor,vert}}$ as Measured with CABAM[a]

$\Delta\phi^{\text{AC}}_{\text{hor}}$	$\Delta\phi^{b_2}_{\text{hor}}$	$\Delta\phi^{\text{AC}}_{\text{hor}} - \Delta\phi^{b_2}_{\text{hor}}$	$\Delta\phi^{\text{AC}}_{\text{vert}}$	$\Delta\phi^{b_2}_{\text{vert}}$	$\Delta\phi^{\text{AC}}_{\text{vert}} - \Delta\phi^{b_2}_{\text{vert}}$
−13	−9	−4	275	271	−4
6	−1	7	−278	−278	0
358	363	−5	1	−3	4
−352	−355	3	−3	0	−3

[a] All values given in µrad.

For both horizontal and vertical angles, the differences between the AC measurement $\Delta\phi^{\text{AC}}$ and the measured beam direction change $\Delta\phi^{b_2}$ are symmetrically distributed around zero, showing no significant bias. The root-mean-square of the differences between $\Delta\phi^{\text{AC}}$ and $\Delta\phi^{b_2}$ is similar for both horizontal and vertical angles, being 5 µrad horizontally and 3 µrad vertically. The biggest difference measured between $\Delta\phi^{\text{AC}}$ and $\Delta\phi^{b_2}$ is 7 µrad horizontally and 4 µrad vertically.

Now we want to show that CABAM can also be used to align a beam to a desired position and direction. We follow the procedure described in Section 3. After coarsely aligning beam $\vec{b}_2$ to two arbitrarily chosen points $\vec{q}_1, \vec{q}_2$, which define our desired beam $\vec{B}$ [Eq. (4)], we proceed by measuring points $\vec{p}_1, \vec{p}_2$ on beam $\vec{b}_2$ and correcting the beam $\vec{b}_2$ position in the near and far fields. After three iterations, we measure the beam position and direction with CABAM: we have aligned beam $\vec{b}_2$ to the desired beam position and direction $\vec{B}$ with (7 ± 3) µm positional and (2 ± 10) µrad angular accuracy. The positional alignment could have been improved by applying more iterations.

5. Conclusion

We have presented a novel and easy-to-implement method to measure both the laser beam direction and position or to align a laser beam to a desired direction and position: CABAM. Our method makes use of a CMM in noncontact mode and a position-sensitive QPD to center the CMM probe sphere in the laser beam. We have verified that CABAM exhibits a positional accuracy of 3 µm and an angular accuracy of less than 10 µrad.

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