A MICROMETRIC POSITIONING SENSOR FOR LASER-BASED ALIGNMENT

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Abstract

The Compact Linear Collider requires 10 µm accuracy over 200 m for the alignment of its components. Since current techniques based on stretched wire or water level are difficult to implement, other options are under study. We propose a laser alignment system using positioning sensors made of camera/shutter assemblies. The goal is to implement such a positioning sensor. The corresponding studies comprise design and calibration as well as investigations of measurement accuracy and precision. On the one hand, we describe mathematically the laser beam propagation, its interaction with the shutter and image processing. On the other hand, we present experiments done with the prototype of a positioning sensor. As a result, we give practical suggestions to build the positioning sensors and we describe a calibration protocol to be applied to all sensors before measuring. In addition, we deliver estimates for measurement accuracy and precision. Our work provides the first steps towards a full alignment system.

INTRODUCTION

The Compact Linear Collider sets a challenging objective for the pre-alignment of its beam-related components: 10 µm accuracy over 200 m (at 1 σ) [1]. To meet such a requirement, we proposed an alignment system based on a laser beam under vacuum as straight line reference and camera/shutter assemblies as positioning sensors [2, 3]. The name of the project was LAMBDA (Laser Alignment Multipoint Based Design Approach) [4].

The goal of a LAMBDA positioning sensor is to provide the position of the laser beam with respect to reference targets with an accuracy of 5 µm (see Fig. 1). To do this, we close the shutter, we capture a picture of the laser spot with the camera and we apply image processing. After the picture capture, we open the shutter in order to let the laser beam propagate until the next shutter.

To validate the alignment system, we developed several prototypes and tested them in different conditions. We performed experiments at short distance (up to 3 m) in order to minimise uncertainty due to laser beam propagation and to focus on sensor performance [5]. As a result, we showed that ceramic was a good compromise between metal and paper for the shutter material, since it gave a laser pointing stability below 5 µm. We also performed experiments over long distance (up to 200 m) in order to estimate uncertainty due to laser beam propagation [6]. As a result, we showed that using a vacuum pipe resulted in a laser pointing stability of 8 µm at 35 m.

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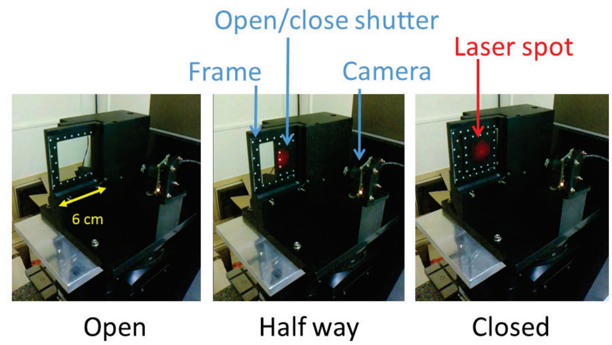

Figure 1: Prototype of a positioning sensor made of a camera, a shutter and a frame. The white disks on the shutter and on the frame are reference targets.

All these experiments dealt with measurement precision. However, in order to fully validate the positioning sensor, we needed to estimate measurement accuracy. We performed further tests which led us to slightly change the model used for the positioning sensor. In this paper, we summarise the theoretical background on which our model is build and we present experiment results regarding measurement accuracy. We also provide a calibration protocol of the positioning sensors and discuss their measurement uncertainties.

THEORETICAL BACKGROUND

Laser/shutter interaction

The model used for the laser beam under vacuum is the Gaussian beam. In our project, the alignment reference is the propagation axis of the Gaussian beam, this is why we will be interested later in determining the laser spot centre.

The laser beam propagates until it is interrupted by a closed shutter, resulting in a laser spot on the shutter surface. Since the camera is not in front of the shutter but on the side (see Fig. 1), we assume that the shape of the laser spot captured by the camera is a two-dimensional elliptical Gaussian curve (see Fig. 2).

The laser spot intensity on the shutter surface can be mathematically described as follows:

$$I(x_s, y_s) = a \cdot e^{-\left[x_{\text{norm}}^2 + y_{\text{norm}}^2 + \frac{2s_{xy}}{s_x s_y} x_{\text{norm}} y_{\text{norm}}\right]}$$

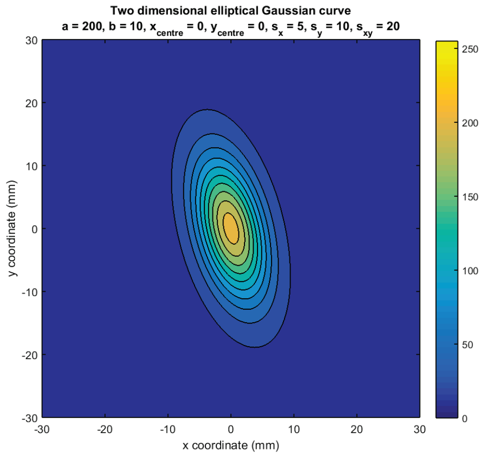

Figure 2: Two-dimensional elliptical Gaussian curve used as a model for the laser spot captured by the camera.

with $x_{\text{norm}} = \left(\frac{x_s - x_{\text{centre}}}{s_x}\right)$, $y_{\text{norm}} = \left(\frac{y_s - y_{\text{centre}}}{s_y}\right)$, (x_s, y_s) any point on the shutter surface in the shutter coordinate system, a the maximal signal intensity, $(x_{\text{centre}}, y_{\text{centre}})$ coordinates of the laser spot centre, (s_x, s_y) the parameters characterising the spread of the elliptic Gaussian curve in radial and vertical directions and s_{xy} the parameter characterising the orientation of the elliptic Gaussian curve.

Furthermore, the interaction between laser beam and shutter is affected by speckle [7]. Speckle adds noise to the laser spot intensity, characterised by a negative exponential probability density function. Thus, for any point of the observation plane, where the light intensity average is $\bar{I}$, the probability p_s of observing an intensity I_s is $p_s(I_s) = \frac{I_s}{\bar{I}^2} e^{-\left[\frac{I_s}{\bar{I}}\right]}$. Since speckle adds noise to the laser spot pattern, determining the laser spot centre is not straightforward. During the image processing, an adjustment is needed between the pixel observations and the two-dimensional elliptical Gaussian curve mentioned above. Such an adjustment brings uncertainty into the estimated coordinates of the laser spot centre.

Camera model

The model used for the camera is based on perspective projection and distortion. Perspective projection maps any 3D point related to the shutter coordinate system to a 2D point related to the camera coordinate system. It is based on 6 parameters for translation and rotation between shutter and camera coordinate systems, and 1 parameter for the camera principal distance. In our project, the distortion model is taken from [8]. It is based on 2 parameters for the principal point, 3 parameters for radial distortion, 2 parameters for tangential distortion and 2 parameters for affinity and shear.

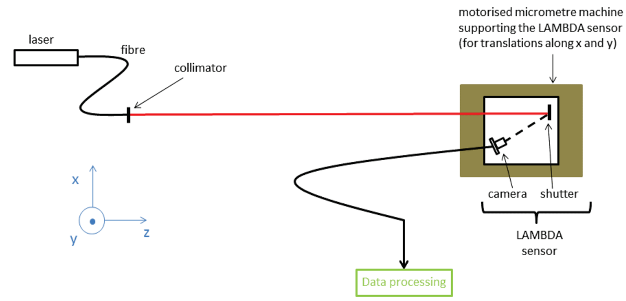

Figure 3: Schematic view of the setup. The distance collimator - shutter was 3 m and the distance shutter - camera was 10 cm.

Image processing

The image processing consists of reconstructing the coordinates of the laser spot centre from the camera chip to the frame coordinate system, which is also the sensor coordinate system. It comprises several steps. On the one hand, the targets located on the shutter and on the frame are processed by ellipse fitting in order to perform a camera auto-calibration. This auto-calibration provides estimates for the parameters of perspective projection and distortion mentioned before, as well as for the parameters characterising the position and the orientation of the shutter with respect to the frame. On the other hand, the laser spot centre is first extracted by two-dimensional elliptical Gaussian fitting. Then, distortion is corrected and the inverse of perspective projection is applied. Finally, a rigid body transformation is applied from shutter to frame.

EXPERIMENT REGARDING MEASUREMENT ACCURACY

Objective

We wanted to estimate the measurement accuracy of one prototype of positioning sensor.

Setup

The experiment was done in an optical lab located in a basement of CERN. There was no vacuum pipe, so the experiment was done in air. However, the optical lab was a closed room with no ventilation so it was a stable environment. In addition, the distance of propagation between the laser source and the shutter was 3 m, which minimised the uncertainty due to laser beam propagation. The experimental setup is presented in Fig. 3.

The laser beam was produced by a HeNe laser and passed through an optical fibre and a collimator. The LAMBDA sensor was made of a camera and a shutter that was in closed position throughout the experiment. The camera resolution was 1280×1024 and its pixel size was 3.6 µm. The shutter was a ceramic plate. The LAMBDA sensor was fixed on a motorised micrometre table allowing radial (along x) and vertical (along y) displacements with 0.1 µm accuracy. The camera and the motorised micrometre table

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were controlled remotely, thus nobody entered the room during the series of measurements. The laser, the collimator and the motorised micrometre table were installed on a marble bench to minimise ground vibration.

We should notice that using such a setup resulted in a rather small laser spot on the shutter surface (diameter around 1-2 mm). However, we showed in [3] that, when the laser beam propagates from 0 to 200 m, the laser spot diameter varies from a few mm to 4 cm. Thus, the present experiment does not tackle any distance of propagation between 0 and 200 m but only the distance of propagation where the laser spot diameter is in the range 1-2 mm.

Protocol

We moved the LAMBDA sensor to 121 positions (from x = -1 mm to x = +1 mm and from y = -1 mm to y = +1 mm). For each position, we captured one picture and we extracted the laser spot coordinates by means of image processing. Finally, we performed an adjustment between theoretical (given by the motorised micrometre table) and measured positions, and we analysed residuals.

Results

In a first iteration, we assumed that the laser beam reflection occurred at the level of the shutter surface. We could see that the measured values were less spread than the theoretical ones, as if there was a scale factor between them. In a second iteration, we assumed that the laser beam slightly penetrated into the shutter material and that the reflection occurred on a virtual plane behind the shutter surface [9]. We could see that the scale factor behaviour disappeared. The standard deviation of the residuals was below 6 µm. In addition, the laser beam penetration into the ceramic plate was estimated to be −70 µm.

We learnt several lessons from this experiment. It provided an estimate for the measurement accuracy of the positioning sensor. It made us slightly change our model for the laser/shutter interaction by taking into account the penetration of the laser beam into the shutter material. It gave us an estimate of how much the laser beam penetrated into the shutter, necessary for a correct reconstruction of the laser spot centre. Finally, it defined a protocol for the future sensor calibration.

SENSOR CALIBRATION

As mentioned in the previous section, a calibration of each positioning sensor is needed before being used. First, the reference targets located on the shutter and on the frame need to be measured before the experiments, for example by a metrology service. Second, the distance of penetration of the laser beam into the shutter material needs to be determined, for example with an experiment similar to the one described above. Third, in order to do the adjustment correctly, correspondences have to be established between the real reference targets and the imaged reference targets. Such a step could be avoided, for example if coded targets are used.

MEASUREMENT UNCERTAINTY OF THE SENSOR

The experiment described above was done with a shutter in closed position. It gave estimates of the measurement uncertainty in the shutter coordinate system. However, we are interested in the measurement uncertainty in the frame coordinate system. Thus, the repositioning of the shutter with respect to the frame plays a major role.

We developed a prototype combining an open/close mechanism and a shutter with paper surface (see Fig. 1). The uncertainty of repositioning was about 2 µm in radial and in vertical directions and 5 µm in depth [3].

Based on error propagation, we could estimate the measurement uncertainty associated to any laser spot centre reconstructed by a LAMBDA positioning sensor. For the paper surface, we found an uncertainty below 13.0 µm in the shutter coordinate system and below 15 µm in the frame coordinate system. For the ceramic surface, we found an uncertainty below 5 µm in the shutter coordinate system and below 8 µm in the frame coordinate system. It should be noticed that since the ceramic shutter was not open/close, the same values as the paper were taken for the transformation between shutter and frame.

CONCLUSION

We studied and developed a new type of positioning sensor to be used for lased-based alignment at micrometre level over long distance (up to 200 m). This sensor was made of a camera and an open/close shutter and was able to provide the position of the laser beam in the sensor coordinate system. We summarised the main aspects of the theoretical background on which our model is built and we presented one experiment regarding measurement accuracy, that highlighted the fact that the laser beam penetrated into the material before being reflected. Based on this experiment, we defined a calibration protocol and we estimated the measurement uncertainty to be below 8 µm for a ceramic shutter with open/close mechanism. This value was encouraging since it was close to the requirement (5 µm).

Our study does not provide a full alignment system but it is the first necessary step towards it. The next step would be to build a prototype of positioning sensor combining ceramic shutter and open/close mechanism. After its validation, the idea would be to build a whole alignment system over 200 m and comparing it with an alignment system based on another principle, for example a stretched wire or a water level as straight line reference. This would require to have a vacuum pipe over 200 m. It would also require to design and develop interfaces between laser-based, wire-based and water-based positioning sensors.

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