LATEST DATA FROM THE LINEAR COLLIDER ALIGNMENT AND SURVEY PROJECT (LiCAS)*

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Abstract

The LiCAS project has developed a prototype robotic survey system for rapid and highly accurate surveying of long linear accelerator tunnel networks. It is aimed at the International Linear Collider (ILC). We show how data obtained during measurement and calibration runs at DESY is used to calibrate one car of the Rapid Tunnel Reference Surveyor (RTRS).

INTRODUCTION

A description of the prototype RTRS and its functionality has been described earlier [1]. This work will focus on the calibration of the robot, since simulations have shown that the dominant sources of errors over long distances will be systematic errors resulting from miscalibration of the surveyor. This calibration is only possible with a good experimental determination of the errors attributable to each subsystem, which we present here along with the calibration and simulation status. The global survey is discussed elsewhere [2].

Figure 1: Laser tracker assisted calibration setup of the RTRS in the DESY test tunnel (June 2008)

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MEASUREMENT PERFORMANCE

Laser Straightness Monitors (LSM)

A detailed description of the LSM system can be found in [3]. The LSM beams are detected by analogue CCD cameras, where various transformations are utilised to remove effects from dust and to take inter-camera reflections into account [4]. A time dependence due to interference patterns between frame grabber channels leading to small oscillatory shifts of the fitted horizontal positions of the beams was found. To compensate for this effect, multiple images (40) are averaged over a period of 120 sec.

However, a drawback of this solution is that the units may move slightly during data acquisition. The reconstruction needs to have all the data provided to it for a particular moment in time. Therefore, a projection to the correct time needs to be made. The FSI sweep is performed three seconds before the first LSM image is taken. As can be seen in figure 2 there is significant motion during the two minutes required to take 40 images.

To create a point for $t = -3$ sec that can be used in reconstruction, a polynomial is fitted to the x or y positions of the beam positions of the 40 images under study. During the least squares process which determines the best fit, an additional constraint can be added which allows us to determine the error associated with the projected point. We give the total estimated errors for the x and y directions of the 12 CCDs present in the RTRS as a function of distance in figure 3. Note that, for all runs and all cameras, the error estimates remain below a $5\mu m$ threshold.

Frequency Scanning Interferometry (FSI)

The LiCAS RTRS has two FSI measurement subsystems, one operating in vacuum ("internal") and one in open air ("external"), whose general characteristics and stability properties have been described elsewhere [5, 6].

The only significant known source of systematic FSI errors, common to all lines is a variation in the reference interferometer lengths. We estimate these using the ratio of the two reference lengths during car-2 calibration and its deviation from the value found during calibration of the reference interferometers.

The largest such difference in ratios is 4.92×10^{-7} (see figure 4), and leads to an error of $\pm 0.635\mu m(stat.) \pm 1.612\mu m(syst.)$ on the first reference interferometer length and slightly less on the second.

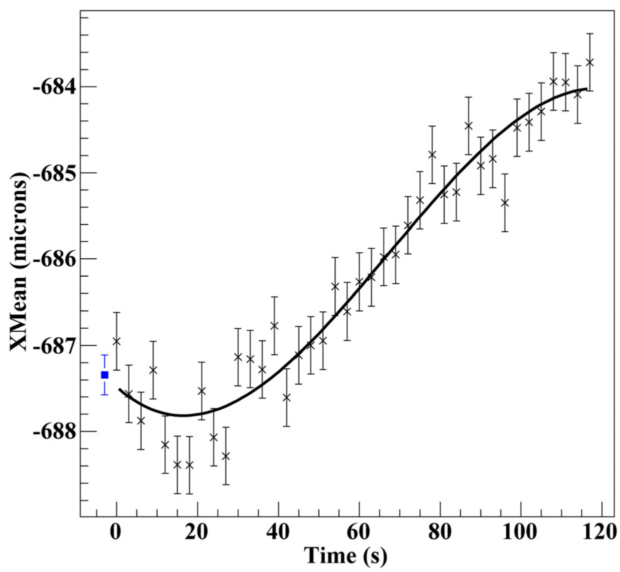

Figure 2: Typical beam motion during data taking. The images are spaced in time by three seconds.

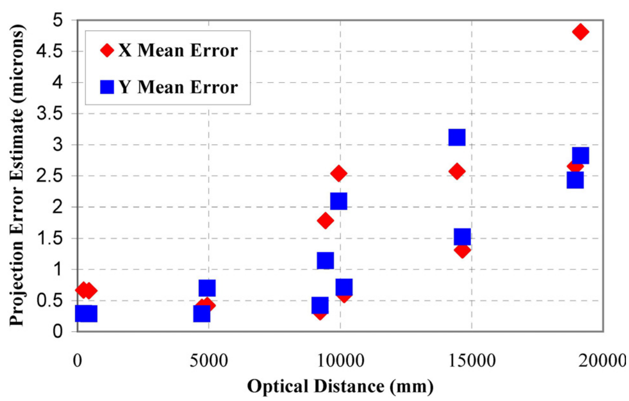

Figure 3: Error vs distance from LSM launch

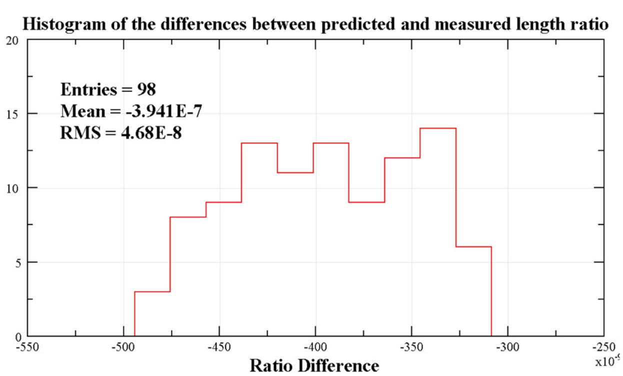

Figure 4: Histogram of the difference between the predicted (from length calibration) and measured length ratio of the two reference interferometers during car-2 calibration

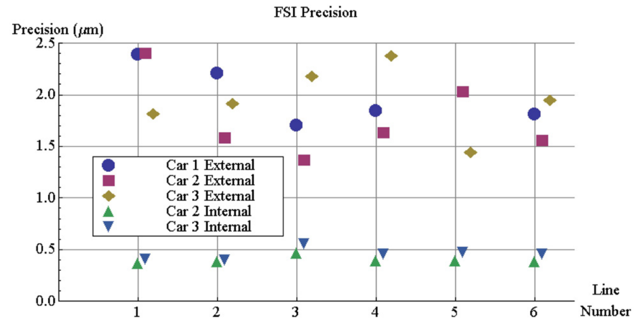

Figure 5: External and internal FSI precision from rapid scan analysis

The statistical FSI errors are determined from dedicated rapid scan experiments and are shown in figure 5. We determine one common set of errors each for internal and external FSI during the car-2 calibration period by taking the largest internal and external FSI line RMS from the rapid scans and the errors of the first reference interferometer. This leads to the following: internal FSI:$\pm 0.559\mu m(stat.) \pm 2.267\mu m(syst.)$; external FSI: $\pm 2.40\mu m(stat.) \pm 0.228\mu m(syst.)$.

SIMULATION AND CALIBRATION

Calibration of the unit, i.e. determination of the positions and orientations of all internal components, various scaling factors, etc., proceeds via a least squares mechanism. In this formalism, we seek the best values for a set of unknown calibration parameters X which reproduce a set of calibration measurements, L, where these measurements have been generated by random spatial translations and rotations of a unit of the RTRS. It is assumed that the functional dependence F of the measurements on the internal parameters is well understood. To find the optimal X one simply minimises the Euclidean norm of the vector $F(X) - L$ weighted by an error matrix P.

We perform calibrations on a car-by-car basis, determining only the parameters of one unit, assuming best estimates for the others and then iterate. Ideally we would calibrate subsystems independently. This will only work if the sub-problem is well-determined, i.e. there must not exist any eigenvector with zero eigenvalue of the design matrix $A = \partial F/\partial X$. Unfortunately, it can be shown that each subsystem (LSM, FSI, tilt sensors) suffers from various non-trivial "symmetries" of this nature, which ultimately represent weaknesses in the design. Improvements to future designs can readily remove these symmetries, both simplifying the calibration requirements (so that no laser tracker observer is required) and improving errors dramatically, since the errors are determined by the "weakest link" in the overall design.

For a relatively small set of 24 calibration runs where only one car is moved while the others remain stationary and are assumed to be roughly in their build positions, a

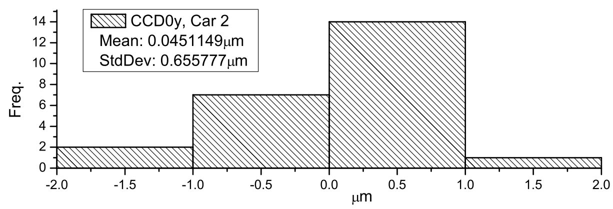

Figure 6: $L - F(X)$ for CCD0y of the LSM subsystem

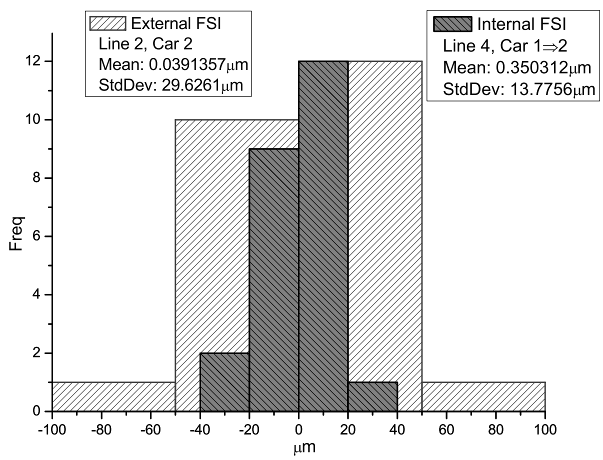

Figure 7: $L - F(X)$ for representative lines of the external and internal FSI subsystems

data vector L with 2197 measurements can be used, along with 50 constraints, to determine 588 unknown parameters in a simplified model. The problem is quite non-linear, requires a careful analysis of constraints and particular numerical care when performing algebraic calculations. During the least squares procedure, calibration positions of the subsystems are seen to converge to values near to those expected.

To measure the level of internal consistency of our model we show the agreement between L and $F(X)$ for some of the critical subsystems in figures 6 and 7. Agreement between the two is good for each subsystem, with typical values of $(F-L)/L \approx 3.3\times10^{-6}$ for the internal FSI system, for example. For the FSI systems the width of the $(F - L)$ distributions exceeds the measured FSI errors. We believe that this is due to inadequacies in the determination of X resulting from improper errors in P, as well as external factors such as wave front corrections or atmospheric corrections not yet considered in F. These distributions are expected to improve with further analysis.

During calibration one must define the elements of X with respect to some common coordinate system. Although this could be arbitrarily fixed by a set of constraints to coincide with a particular element, this is not optimal. The optimal configuration X^* minimises the trace of the covariance matrix, a problem known as the "free network" problem in geodesy and "bundle adjustment" in photogrammetry (see [7] and references therein). Failure to take this approach can lead to unrealistic error estimates. We are currently in the process of implementing this solution, and we expect results shortly.

FUTURE WORK

Calibration efforts are ongoing and agree on the micron scale. The implementation of free network/inner constraints should lead to the best estimation of the entire accuracy of the RTRS, and preliminary results have thus far been encouraging.

The techniques we have developed in the calibration of the RTRS will help us to improve the designs of both the LSM and FSI subsystems, allowing them to self-calibrate properly and make full use of the precision measurements given above.

REFERENCES

[1] The LiCAS-RTRS - A Survey System for the ILC, A. Reichold for the LiCAS collaboration, Proceedings of the 10th biennial European Particle Accelerator Conference, Edinburgh, UK 26-30 June 2006.

[2] Simulation of the Alignment of Linear Accelerators, John Dale and Armin Reichold, PAC2009.

[3] First measurements from the Laser Straightness Monitor of the LiCAS Rapid Tunnel Reference Surveyor, Gregory Moss for the LiCAS collaboration, Proceedings of the 10th International Workshop on Accelerator Alignment, February 11-15, 2008 KEK, Tsukuba, Japan.

[4] First Data From the Linear Collider Alignment and Survey Project (LiCAS), A. Reichold for the LiCAS collaboration, EPAC2008.

[5] The LiCAS Rapid Tunnel Reference Surveyor - The Status after Commissioning, A. Reichold for the LiCAS collaboration.

[6] Initial Calibration and Stability Results from the LiCAS RTRS FSI System, John Dale for the LiCAS collaboration, Proceedings of the 10th International Workshop on Accelerator Alignment, February 11-15, 2008 KEK, Tsukuba, Japan.

[7] Bundle Adjustment: A Modern Synthesis, Bill Triggs, Philip McLauchlan, Richard Hartley and Andrew Fitzgibbon, in Vision Algorithms: Theory and Practice, 2000, pp. 153-177, ISBN 978-3-540-67973-8.