VALIDATION OF AN OPTICAL WPS SYSTEM

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Abstract

For the Compact Linear Collider (CLIC) project an active pre-alignment system is planned to be used with over 90.000 wire position sensors (WPS). Therefore low cost solutions are studied. Open Source Instruments Inc provides a charge-coupled device (CCD) camera based WPS.

This sensor has been tested for its different characteristics, such as resolution, precision, stability, linearity, dynamic range and absolute calibration. A particular focus has been put on tests with different types of wires. In this paper, the sensor design is presented, followed by the results of the tests carried out with the sensor and the wires.

INTRODUCTION

Within the framework of the Compact Linear Collider (CLIC) study at the European Organization for Nuclear Research (CERN) a new alignment concept has to be proposed in order to achieve the demanded alignment tolerance of 10 µm over a sliding window of 200 m along the accelerator. For the transverse prealignment of the machine, overlapping stretched wire systems are proposed [1]. In order to use the system for vertical measurements, the vertical wire catenary will be modeled by using hydrostatic levelling systems. Different wire detection sensors are being qualified for this challenge. In cooperation with CERN, Open Source Instruments Inc. is developing a low cost, optical wire position sensor. This sensor has been tested in combination with a new, high performance wire. This wire is a Vectran fibre strand which has mechanical characteristics that are very interesting for the use in alignment systems. Thus its weight of only 0.133 g/m, the wire is more robust as presently used carbon-peek or fishing line wires. It has almost no creep, a very low moisture absorption rate and a linear mass which is about factor 0.6 smaller than the carbon-peek wire. With the chosen infrared (IR) flash array, the wire is difficultly detectable with the optical sensor and in consequence some changes had to be applied to the detection routines.

DESIGN

The design of the optical WPS has been specified with the following parameters, derived from the constraints of the CLIC prealignment system [1].

- ± 5 mm dynamic range in X and Y axis
- 5 µm rms absolute accuracy
- 2 µm rms precision

As shown in Fig. 1, the sensor is made of two cameras that are taking pictures of the same section of a stretched wire from two different viewing directions. The calibration of each camera allows for each image the determination of a plane that contains the centre line of the wire. By intersecting these two planes, the centre line itself can be calculated. This centre line represents the wire. The intersecting line concept is shown in Fig. 1 with the blue fields of view of the cameras. The cameras are installed on the vertical support of the sensor body and are mounted with an angle of plus and minus 31 degrees each from the horizontal direction. This results in a slightly better configuration for the determination of the vertical direction and therefore the precision in vertical is about factor 0.6 better than the horizontal plane. Electronics and flash light source are also installed on the sensor base plate. The flash used to illuminate the wire is an IR light-emitting diode (LED) array.

The mechanical interface with a geodetic network is provided by a kinematic ball mounting interface.

Figure 1: OSI WPS-1B generation sensor

This allows the installation of the sensor on a Brandeis CCD Angle Monitor (BCAM) base mounting [2]. The installation repeatability with the same device achieved by using a torque wrench is 1 µm [3]. The sensor is calibrated relative to the ball mounting and provides an output of horizontal and vertical coordinates.

TESTS

In order to validate the sensor, the proposed series of tests have been divided into two parts. The first step was the validation of the sensors in the same way as it was done by Open Source Instruments [2]. The test series were based on measurements on a stainless steel pin or carbon-peek wire. The following tests have been carried out:

- stability measurements on stainless steel pin
- stability measurements on carbon-peek wire
- full and dynamic range measurements
- linearity measurements
- repeatability of the measurements

The second step was the validation of the sensors also with the Vectran wire and by using a common calibrated bench with kinematic ball mountings for each of the sensor base plates installed:

- stability of three sensors on the same wire
- absolute calibration check of the sensors

Equipment

A calibrated bench with supports for three optical wire position sensors was used for all measurements on a stretched wire. The calibration of each support on the bench is known to better than ± 3 µm. For stability tests, a static setup has been chosen and the bench has been fixed to a wire stretching unit with a fix end and a pulley end with a weight of 10 kg.

The second setup has been used for all other configurations where the wire was moved in the field of view of the sensor. To control the wire movement, high precision linear stages have been installed in order to move the wire independently in vertical and horizontal direction. The stages were mounted perpendicular on two granite tables allowing the precise positioning of the wire inside the sensor's field of view. Linear encoders on the stages gave the stage position in sub-µm resolution and a bi-directional repeatability of 0.1 µm.

Stability on steel pin

The idea of a stability measurement is based on the calibration concept of the sensor [2]. The calibration is carried out with respect to a stainless steel pin that is referenced with a coordinate measuring machine (CMM) and displaced in the field of view of the sensor.

For this test a steel pin was glued to the sensor support and the samples were taken over a period of 5 days with a total of 70.000 measurements. The sensors showed a series of outliers at reproducing distances of 1 µm and 3 µm from the average value as shown in Fig. 2. The problem was that they were not clearly to be identified, as they varied only by some micron from the average value. Statistical methods, averaging and the number of samples helped to identify that these were real outliers. During further investigation, this problem had been solved, as the error sources were identified. The offset was due to insufficient number of decimal places in the calculation software.

Stability on Vectran wire

Stability tests with a stretched wire are more delicate as the stability of the wire has to be monitored as well. The calibrated test bench provided the three sensor setup and was used to measure the stability of the sensors with the Vectran wire in order to be able to determine a possible change in the reference wire. The analysis showed that the setup was stable within the measurement precision. Fig. 3 shows the distribution of the deviations from the average value for the sensor P0200 in horizontal direction. There are four lines visible at distances of approximately 3 µm between each line. The observation of steps from measurements on the stainless steel pin are confirmed during these measurements. The larger number of outliers is due to the difficulties in the Vectran wire detection. The stability is about factor 7 worse using the Vectran wire compared to a steel pin setup [4].

Absolute calibration check

Checking the calibration is difficult when not repeating the calibration on a CMM and having a precision better than used for the calibration itself.

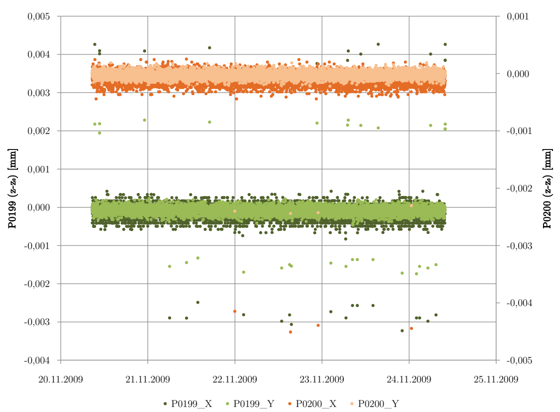

Figure 2: stability measurements on steel pin

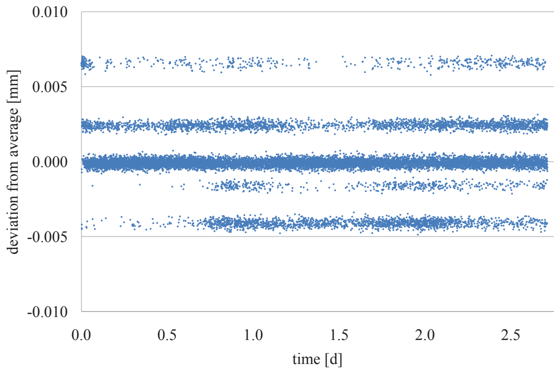

Figure 3: stability measurements on Vectran wire

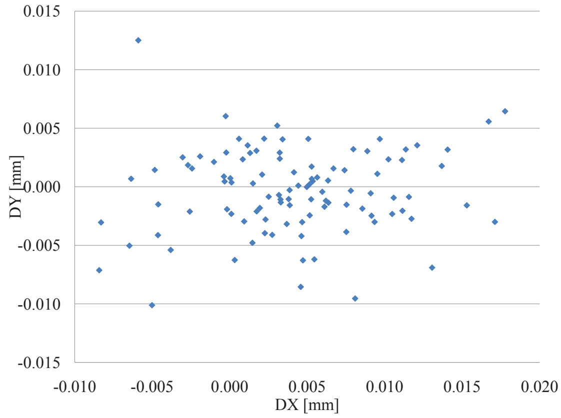

Figure 4: deviation to straight line

With the infrastructure available, it was chosen to check the calibration by comparing different sensors on the calibrated test bench that can host three sensors. The sensors measure the same stretched wire at the same time in a static setup.

By assuming that the calibration of all sensors is correct, the resulting three coordinate pairs should form a straight line within a calibration tolerance of ± 3 µm. A standard deviation of 4 µm in vertical and 7 µm in horizontal direction was obtained. The factor of approximately 0.6 between the horizontal and vertical axis is due to the camera configuration. The deviations are plotted in X and Y direction on the Fig. 4.

This test reveals the precision of the sensors as they are checked against each other without any external effects to be taken into account. The result depends only on the quality of the calibration itself. The disadvantage in this configuration is that possible common and systematic effects of the sensors are also eliminated. The results become more optimistic in this case.

The difference between the obtained precision, the theoretical and the precision obtained by Hashemi on a steel pin gave additional evidence to a problem in the detection of the Vectran wire [2]. Detailed analysis by Open Source Instruments of the images producing the offsets of approximately 3 µm showed that the edge detection routine was not always able to follow the complete wire edges in the images. Some modifications of the software have been made by Open Source Instruments in order to solve this problem.

Range and linearity tests

The range and linearity tests have been carried out using the linear stages that are displacing the wire throughout the range automatically. This has the advantage that the measurements are carried out over night without anybody in the laboratory who could disturb the measurements. In addition, a larger number of points, in our case a grid of 1 mm by 1 mm, can be measured. The obtained deviations are in the same order of magnitude than the ones for the calibration check. This means that no significant non-linearity has been detected, taking into account that these tests have been carried out so far only with the old software and the Vectran wire detection problem.

It is expected that the sensor is better than the precision found. In order to validate this assumption CERN needs to repeat the tests using the new software. As the linear stages were only a loan, CERN is about to purchase a new linear stage system which is designed to allow sub- µm movements. At the same time, the validation concept will be modified, as the new system will be a XY stage system displacing the sensor over its measurement range and keeping the wire in a stable position.

Resolution and edge detection

During the tests, two problems were identified that limited the exploitation of the sensor. The resolution of the sensor's coordinate output was limited by the number of decimal places available during the calculation. At the same time, the edge detection algorithm had to be modified in order to stitch together the edges of the wire along the image in case it is detected as a continuous line.

A stability test on Vectran wire was used to validate the improvements in the software. Fig. 5 shows the resolution of the sensor in both measurement axes of one sensor. The resolution is now at 0.1 µm.

During first tests, large outliers in the measurements showed the failure of the edge detection algorithm. Therefore the number of outliers is a criterion to qualify the reliability of the method. For a set of measurements with four sensors and 30.000 measurements of each sensor, only 1 out of 25.000 measurements fails the edge detection. Therefore it can be concluded that the algorithm is working reliable.

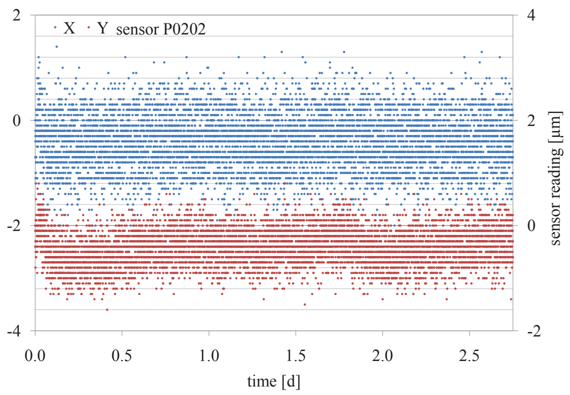

Figure 5: software validation - resolution

FUTURE MODIFICATIONS

The source of the Vectran wire detection problems is the fact that the Vectran fibre is almost transparent to IR light which is used to for diffuse illuminatation of the wire by reflection from the back. This leads to a relatively poor contrast in the images and problems in the edge detection algorithm.

There are several possibilities to solve this inconvenience. One approach is dying the wire in order to make it opaque to IR light. This will have an impact on the mechanical properties of the wire. Tests are ongoing concerning this subject. Another approach is the use of a different light source. Some preliminary tests showed that a green LED array already enhanced the contrast to an acceptable level. Changes to the edge detection routines now give a reliable version of the implemented edge detection in the software as it is able to detect fractions of the edges and joins them if needed. A combination of the new software and the green LED can be a stable and reliable future solution.

The next version of this sensor should, beside mechanical modifications, include some essential improvements concerning the acquisition frequency and might even provide redundancy in the sensor's measurements. The actual acquisition frequency of approximately 1 Hz is decreasing with every sensor installed on the data acquisition system as the sensor's readout is made sequentially. This does not allow the monitoring of the wire‘s Eigenfrequency which is mandatory to control the stability of the wire and also can be used to see if the wire is not touching between its anchor points. Already the acquisition of the two images for one sensor is delayed by the exposure time of the first image by at least 0.2 s in the current version. The installation of a third camera can provide a better intersection of the wire and provide redundancy for the calculation of the wire position.

The radiation tolerance of the device is not one of the important issues at the moment, but this should be kept in mind when working towards a final solution. All components are exposed to radiation as all electronics are directly installed on the sensor body and are not remotely in a radiation protected area. The cameras will have to be chosen in order to withstand the radiation parameters in the design specification.

CONCLUSIONS

The optical WPS from Open Source Instruments has been tested in several steps at CERN. The approach of a validation in the same conditions as at Open Source Instruments, e.g. with a steel pin, showed decimal propagation problems in the software which have been solved.

The use of Vectran wire was an element added to the check measurements with this sensor. A robust edge detection interpretation has been implemented with the software now which cut the failure rate of the wire detection by factor 100 and improved the precision of the edge detection by factor 2.

Linear tables for the wire position sensor validation will be installed at CERN and allow a sensor check with sub-µm resolution.

Now as the sensors have started to develop towards a serial product they are showing their full potential. The implementation of a next sensor generation is planned for 2011 based on the results of the presented tests.

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