THE LHC COLLIMATOR SURVEY TRAIN

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Abstract

Prompt radiation created during the beam cleaning process of the LHC will lead to highly activated beam line components in the cleaning insertions [1]. The ALARA (As low as reasonable achievable) principle is restricting the intervention time in these areas to an absolute minimum and conventional alignment methods will clearly exceed the time limits. Based on the inspection train TIM (Train Inspection Monorail) the survey section has developed a dedicated train module allowing remote controlled measurements of the radioactive components by means of digital close range photogrammetry and stretched wire measurements. The prototype is finished and tests in the LHC mock-up are showing first results.

INTRODUCTION

The beam cleaning insertions in point 3 and 7 of the LHC will become one of the most radioactive zones in the LHC. It was obvious that standard alignment measurements will no longer be possible due to the high radiation level of up to 4mSv/h. The concerned zone is a 500m long straight section of the LHC tunnel with 37 collimators and 26 reference magnets to be measured. The precision should be comparable to the conventional methods in the other zones of the LHC. Conventional measurements would take 4 days for a team of 3 people. The measurements must either be extremely reduced or executed remotely controlled. Reducing the measurements is not considered as an option, as the collimation system is one of the most important parts of the machine protection system.

The basic strategy was to use as many off the shelf components as possible. Various options have been studied, and finally a combination of two different techniques has been chosen. The system is based on a MoveInspect HR photogrammetric measurement system from AICON 3D Systems. This is a fast, precise and non-tactile way to measure the fiducials of the activated collimators. This system is limited to a relatively small volume and a considerable effort is needed to cover the 500m of LHC tunnel.

In order to cover the whole zone, a stretched wire reference is used. More precisely, five overlapping and permanently installed wires are used to connect the different acquisition volumes of the camera system. The aim is to measure the position of the collimators with respect to the surrounding reference quadrupole magnets at the extremities of the wires. The position of the quadrupoles is considered to be the reference.

TRAIN CONCEPT

The train itself is a modular inspection train system called TIM (Train Inspection Monorail) developed by EN/HE Group in order to make remote controlled visual inspections and radiation surveys in the LHC. TIM is composed of two basic modules, the traction wagon and the battery wagon. Depending on the task one or more custom sensor or inspection wagons are added. In the case of the survey train 3 additional modules are added.

- The Sensor wagon carrying the measurement equipment
- The control wagon carrying the infrastructure for the sensors
- A camera wagon with an auxiliary camera for visual controls

The train is using the existing monorail which was installed at the times of the previous accelerator and is controlled via an EDGE (Enhanced Data Rates for GSM Evolution also known as Enhanced GPRS) network which is available all along the LHC. The bandwidth and the delay of the EDGE network is not suitable for a measurement application and so the train is -for this application- fully controlled by WLAN. Collision sensors are installed on each extremity of the train in order to stop the train automatically when people or obstacles are detected. These sensors are part of a security chain together with emergency stops on each wagon of the train as well as on the control console. The link between the train wagons and the console is made by a WLAN security communication. In case of a loss of communication or break of the security chain, the train stops automatically.

Each wagon is equipped with profinet I/O cards permitting to control different device types and reading of the associated sensors. Two 24 Volt batteries give an autonomy of about six hours. Furthermore, the sensitive parts of the train are protected by an UPS (Uninterruptible power supply) in case of voltage variations or power loss.

PRINCIPLE

The position of the collimators will be measured at the same time in the vertical and horizontal direction with respect to the position of the reference quadrupoles using the following principle:

- A photogrammetric system will measure the position of the collimators fiducials with respect to a stretched wire;
- As the wire cannot be measured directly by the photogrammetric system, wire sensors are used to detect the position of the wire. The wire sensors are also equipped with targets and measured by the camera system in the same images as the collimators. This allows calculation of the position of the collimators with respect to the wire.
- The reference qudrupoles are measured exactly in the same way with respect to the same wire. This allows the calculation of the collimators with respect to these quadrupoles.

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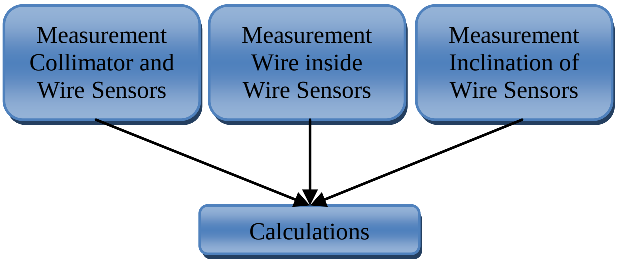

Figure 1: Measurement Flowchart

The wire sensors are mounted on movable arms on the train which is necessary to compensate the position variations of the monorail which has been installed for transport reasons already at the times of the LEP. The rail has deviations of ± 100 mm with respect to the installed wires. These movable arms are part of an active and autonomous system which keeps the wire always at the nominal position inside the range of the wire sensors.

This enables the train to travel on the monorail with the sensors always on the wire. The sensors will only be taken off to pass the pillars. Figure 3 shows the two movable arms around the wire with the camera frame in the background and the collimator targets in front. One single shot of the cameras is needed to measure the collimator with respect to the wire. Redundancy is given by the four cameras and all points have to be measured by at least three cameras.

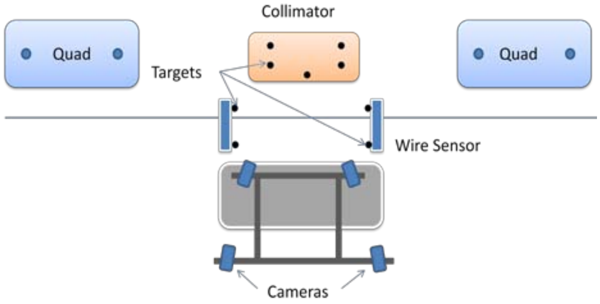

Figure 2: Details of the configuration

INSTRUMENTATION

Photogrammetric system

The core module of the sensors is the photogrammetric system called MoveInspect HR from AICON 3D Systems. It is delivered with 4 AVT Marlin cameras Type F-201 with a resolution of 2 MPixel and an approximate focal length of 6.5 mm in an industrial IP65 housing. A Syncbox is connecting the four cameras and the acquisition PC via IEEE 1394 Fire Wire. A carbon calibration panel is used to calibrate the inner and relative orientation of the cameras which are mounted on an aluminium profile frame. The calibration is made directly in the tunnel, right before the measurements with the full train installed. A second calibration at the end of the measurement campaign is used to validate the measurements. No simultaneous calibration will be calculated during the measurements. The calculation is then not anymore based on a bundle adjustment but on a adjusted intersection with fixed orientations. This allows a single snap with the four cameras to calculate the results. Depending on the configuration the manufacturer quotes a precision up to 20 µm for a volume of 1 m³. These values could be confirmed during the reception tests but due to the configuration on the train 50 to 80 µm are more realistic.

Table 1: Camera Specifications [4]

Type	AVT Marlin F-201B
Chip	CCD Sony ICX274
Resolution	1628x 1236 Pixel 8 Bit
Pixel size	4.4 µm
Focal length	6.5 mm

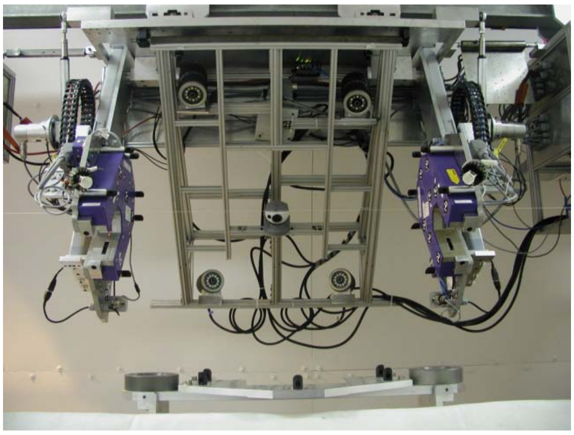

Figure 3: Installed Move Inspect System

The use of a photogrammetric system means also that the points to be measured must be permanently equipped with photogrammetric targets resisting the high radiation level. This is not evident as the usual photogrammetric targets are retro-targets made from glass and resin. Both materials won`t resist for a long time. Non-retro targets are an alternative solution but are usually made from white stickers on aluminium or steel target bodies. In this case the glue is the weak point of the target. Figure 4 is showing a CERN style radiation hard target. The targets are made 100% from anodized aluminium and show the same contrasts as commercially available non-retro targets. The body is precisely machined, satined and black anodized. The target point itself is anodized but not colored and inserted into the body after cooling down in liquid nitrogen. The mechanical centering of the target dot is with ±12µm for the 10% tested sample comparable to commercial ones. For each collimator 5 targets are installed on an adapter plate mounted to the fiducial supports. A dedicated photogrammetric fiducialisation has been made for all collimators showing deviations from nominal up to 80 µm which is in the range of the machining precision for the supports.

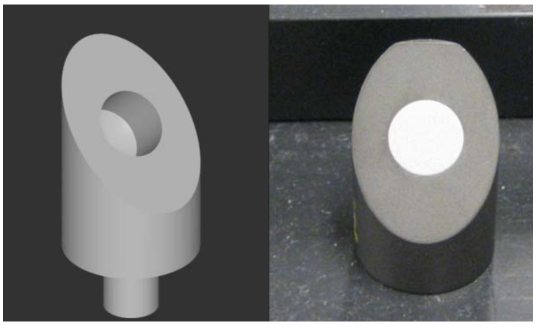

Figure 4: Photogrammetric targets

Wire sensors

The used sensors are laser micrometers with an open measurement field of 35 mm by 35 mm which is large for these kinds of sensors. The software of these sensors has been modified in order to measure the relative distance between the wire and a reference pin representing the origin. The reference pin is the central object in a sensor support with 6 photogrammetric targets and an inclination sensor which is used to orient the system to the local vertical. The wire sensors are AEROEL Xactum XLS 35-XY Laser Micrometer. The principle is based on a rotating polygonal mirror creating a band of laser light, crossing the measurement field and detected on the opposite side of the sensor. Every object in the laser is detected as a shadow so diameter and position can be calculated. The full range linearity is less than 2 µm and an invar reference window together with several temperature sensors ensure a permanent self calibration. The sensors are controlled by a TCP/IP connection and deliver 200Hz measurements. The embedded software has been modified to allow the relative distance measurement between the wire and the reference pin.

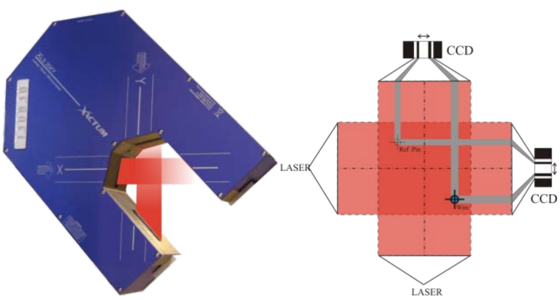

Figure 5: XLS Measurement principle

The inclination sensors are Wyler Zerotronic sensors type 3/3CK-13-097 with a range of ±5º. The two sensors are connected to a levelmeter 2000 readout unit which is controlled by a RS232 connection.

The longitudinal position of the train is measured using a rotation encoder with a resolution of 60 µm on the monorail. The precision is only depending on the slip of the wheel on the rail. Relative longitudinal displacements can be made very precisely and tests have shown that the needed precision of 1mm can be ensured.

All instruments have been adapted by modifying the software and the power supply provided by the train.

Wire

The fact that the vertical direction is measured at the same time makes a precise modelization of the wire sag necessary. The used wires are supported by 10 permanently installed pillars along the measurement zone. The sag is modelled as a catenary with four parameters for each wire [3]. The tension and the linear mass are constant while the length and the height difference depend on the wire. This gives a straight reference for the measurement of all collimators and quadrupole magnets in the zone.

The pillars and fixations are similar to those of the LHC inner triplet monitoring system. The only difference is the fact that 5 overlapping and unprotected wires are used. The configuration in the tunnel does not allow a wire protection tube. There is a significant risk for the wire to be damaged or broken due to other interventions on the collimators or magnets. This excludes the carbon-peek wire used for the inner triplet monitoring system, because it is extremely fragile. The used wire is a 1200 denier Vectran HT fiber strand which offers some interesting advantages compared to the carbon-peek wire. The wire is much more robust, has almost no creep and its linear mass is about a factor 0.6 smaller [2]. This reduces the sag and the tension to be applied. The whole system allows a rather fast replacement of the wires if broken or damaged.

OPERATION

After the start-up and calibration in situ, the measurement sequence is started by the operator. The train will carry out the measurements automatically until the system demands an operator intervention, which will be the passage of the next pillar.

The sequence starts with the declaration of the actual object to be measured and executes the following steps:

1. Stability test for the inclination sensors to control the stability of the train.
2. Stability test for the wire sensors to control the stability of the wire.
3. Triggering of cameras and simultaneous acquisition of all other sensors
4. Repetition of wire stability test to validate the measurements
5. Calculations
6. Positioning in front of next object to be measured

Calculations

The photogrammetric system is commercial and no further photogrammetric calculations are needed. The system delivers directly 3D coordinates via a TCP/IP server application. Starting from the 3D coordinates two best fit transformations are needed to transform the measurements of the wire sensor into the camera coordinate system. An axis alignment and the correction of the sag is needed to obtain the needed horizontal wire offsets and the vertical height differences. All these operations are made by the train software. Two independent input files for the CERN adjustment software LGC++ are created and calculated on every measurement step. This allows checking for coherence directly during the measurement campaign.

The 3D coordinates delivered by the camera system contain the five collimator targets and six targets on each of the wire sensors. The sensor supports of the wire sensors have been calibrated and the installed reference pin is the origin in this calibration system. Furthermore, the six photogrammetric targets as well as the inclinometer support and the misalignment of laser axes themselves have been calibrated. The next step is to transform these points including the measured wire into the 3D coordinate system of the cameras using the six identical target points on the sensors. Then the axis alignment can be made to the wire and the local vertical as measured by the inclination sensors. As a final step the sag and slope of the wire is corrected and all points are in a coordinate system properly aligned with the wire and the local vertical. These coordinates are then transformed into horizontal wire offsets and height differences which can be treated in the standard way using LGC++.

SOFTWARE

The software developed for the train project has been made using LabVIEW. The software is divided into two parts, the sequencer running on the train and communicating with instruments and the remote panel giving information to the user positioned outside the tunnel. The application communicates with the PLC on the train using the “Fetch-Write” protocol from Siemens through TCP-IP. The other instruments in the systems (ie MoveInspect Camera system from AICON, Wyler Zerotronic inclination sensors, Aeroel XLS35 laser micrometer) have been controlled using separate homemade drivers, communicating either through TCP or RS232 protocols.

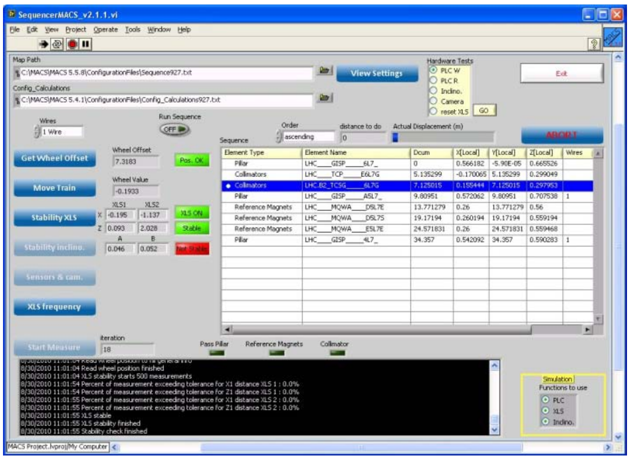

Figure 6: Sequencer view

The sequencer is the main software and takes over the control of the whole train once activated. The remote panel gives the operator the progress and status of all running applications. This includes status of all sensors, results of stability tests, measurements and results. In addition to the train software some other programs are used. The AICON MoveInspect software for the photogrammetric system, the CERN SU software Chaba for transformations and LGC++ are used finally for the calculation of the alignment.

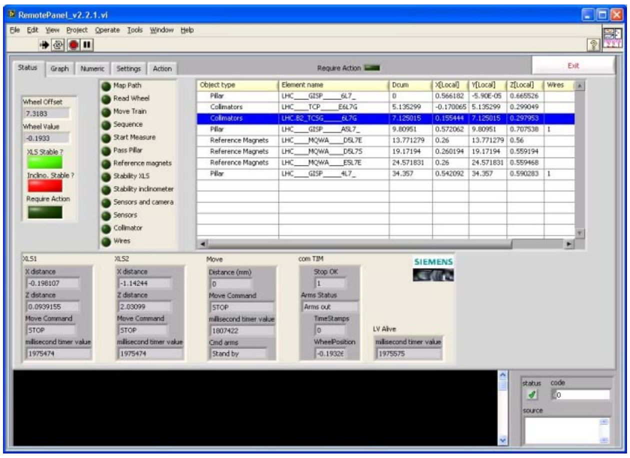

Figure 7: Remote Panel view

STATUS AND FURTHER DEVELOPMENTS

The hardware in the tunnel is fully installed and tested. Preliminary tests in the tunnel have shown that all wires can be followed automatically and all sensors stay well in their range. The hardware of the train is operational and the software is being finalised. A 40 m long real scale mock-up is available to carry out the final tests.

Some details still need to be reinforced, like the aluminium profile frame. Once the configuration is fixed and the experience shows that the optimum is reached, it would be justified to replace this frame by a carbon fibre structure in order to avoid problems due to the dilatation of the material. For the moment, this configuration is sufficiently stable between two calibrations. Repetition tests of several days have shown that the inner and relative orientation is not significantly changing. The coordinates in the object space have been compared using different calibrations and the variations are around 30 µm which is in the order of the measurement precision.

Handling and installation in the tunnel is also a point to be optimized in order to reduce the intervention time in the tunnel.

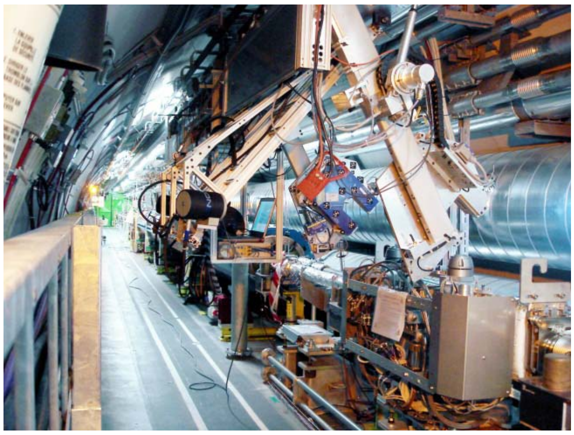

Figure 8: Installed train in front of a collimator

CONCLUSION

The LHC collimator survey train is not comparable to other train projects but it offers a great solution to carry out well defined measurements where dose rates prevent conventional measurements. The combination of state of the art optical measurements with the stretched wire as reference gives a stable and robust combination with 90% commercially available equipment. The precision is a compromise between the needs and a reasonable configuration and, of course, the budget. The system is designed to be precise to 0.2 mm and comparison tests will show in the coming weeks the real achievable precision.

The first ideas for a general LHC survey train exist and once the collimator train is fully operational this would be an interesting new project.

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