Development of an Optical Wire Position Monitor

Open Source Instruments, Inc.
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Outline:

- Introduction, History, LWDAQ
- Description
- WPS1
- Wire
- Performance, Calibration
- Conclusion
- Discussion
The history of the collaboration with CERN:

Detector monitoring:
- Used in all the four LHC experiments.
- Simple and cheap concept
- Radiation hard with in the LHC experiment requirements
- Three ball support
- Efficient DAQ concept

Applications @ CERN
- ATLAS operates 1000 BCAM
- ALICE around 80 devices
- CMS magnet alignment
- LHCb rich1, rich1 shielding

BCAM, Brandeis CCD Angle Monitor
- The angular resolution of a BCAM camera is 5µrad or better at all ranges
The DAQ concept:

- Multiplexer 1...10 Devices
- LVDAQ Driver Board 1...8 Devices or MUX
- TCP/IP

The LWDAQ software is a combination of analysis routines compiled from Pascal source code by GPC (GNU Pascal Compiler) and TCL/TK (Tool comand Language/Tool Kit).

TCL/TK interpreter, called the *Wish Shell*, exists for almost every operating system.
Calibrated sensors are currently tested on the BE/ABP/SU Optics, Texas Instruments CCD, 1 Pixel 10 µm.

Illumination Nine-LED Array (A2014)

Enclosure

Readout Socket, RJ45 connector for the LWDAQ Readout and Powering

Baseplate, including the kinematic mount; M4 mounting screw
### WPS1 Field of View

The nominal position of the optical center, in WPS local coordinates, is \((38.0, 62.4, -5)\) in mm.

#### Properties of the WPS1-B Optics:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture-CCD</td>
<td>10 mm</td>
</tr>
<tr>
<td>Pivot-CCD</td>
<td>10.4 mm</td>
</tr>
<tr>
<td>Aperture Diameter</td>
<td>200±5 (\mu)m</td>
</tr>
<tr>
<td>Aperture Centering</td>
<td>±100 (\mu)m</td>
</tr>
<tr>
<td>Lens Focal Length</td>
<td>9 mm</td>
</tr>
<tr>
<td>Focal Point of Lens to CCD</td>
<td>11 mm</td>
</tr>
<tr>
<td>Flat of Lens to CCD</td>
<td>12 mm</td>
</tr>
<tr>
<td>CCD Width</td>
<td>3.4 mm</td>
</tr>
<tr>
<td>CCD Height</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>CCD Pixel Size</td>
<td>10 (\mu)m × 10 (\mu)m</td>
</tr>
<tr>
<td>Field of View</td>
<td>±160 mrad × ±110 mrad</td>
</tr>
<tr>
<td>Aperture Height Above End Plate</td>
<td>15 mm</td>
</tr>
<tr>
<td>Aperture to Front of CCD Mounting Plate</td>
<td>5 mm</td>
</tr>
</tbody>
</table>
Horizontal Edge Pixels in Image of Carbon Fiber Wire.

Left: the edge pixels shown in gray-scale to indicate absolute value of horizontal derivative.

Right: the edge pixels used in the derivative analysis for each edge are marked with colors.

Carbon fiber wires tend to fray. Individual fibers separate from the wire, and the wire starts to untangle. To constrain these fibers, the wire manufacturer wraps the wire with two thin plastic threads that wind in opposite directions. The pictures show wires with an approximate thickness of 700 μm.

With two thin wrappers in opposite directions, we estimate that the effect of the wrapper upon both the capacitive WPS and our proposed optical WPS will be less than 3 μm.
Wires for an Optical WPS

New wire from Mammutec available
(Monofilaments Vectran, Paraloc, )

Further candidates to be studied...

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm³)</th>
<th>Strength (GPa)</th>
<th>Modulus (GPa)</th>
<th>100-m Sag (mm)</th>
<th>CTE ppm/K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Fiber</td>
<td>1.8</td>
<td>3</td>
<td>300</td>
<td>7.5</td>
<td>~0.5 Longitudinal</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.7</td>
<td>0.5</td>
<td>70</td>
<td>68</td>
<td>25</td>
</tr>
<tr>
<td>Tungsten</td>
<td>19.3</td>
<td>1.5</td>
<td>400</td>
<td>160</td>
<td>4</td>
</tr>
<tr>
<td>Steel</td>
<td>7.5</td>
<td>1</td>
<td>200</td>
<td>94</td>
<td>17</td>
</tr>
<tr>
<td>Copper</td>
<td>8.9</td>
<td>0.2</td>
<td>120</td>
<td>560</td>
<td>17</td>
</tr>
<tr>
<td>Vectran</td>
<td>1.1</td>
<td>2.7</td>
<td>70</td>
<td>5.1</td>
<td>&lt;20</td>
</tr>
</tbody>
</table>

Vectran fiber strength is 27 g/denier. A one denier fiber is a fiber 9 km long that weighs one gram. The density of Vectran is 1.1 g/cm³, so a 1-denier fiber has diameter 10 μm and cross-section 10⁻¹⁰m². The breaking stress is therefore 2.7 GPa, which compares well with the 3-GPa breaking strain of carbon fiber.
Physical Influence on a Wire

Sag $s$ of a wire with constant mass:

The ideal wire would show a clear linear elastic limit and would be insensitive regarding the following Physical Properties:

- Temperature
- Humidity
- Creeping, aging effects
- Gravity
- Radiation

Wires are not showing a clear liner elastic limit given by the various uncertainties (e.g. during the tensile tests)

Wire monitoring in order to study and describe the various influences. Requires the study of possible sensors and their implementation
New wire support for the Tensile machine, developed from SU

(Monofilament wire requires special support due to friction between filaments)

Sample temperature 22 °C

Speed Step 1 5.00 mm/min

<table>
<thead>
<tr>
<th>Tensile tests on wires</th>
<th>$F_m$ [N]</th>
<th>$R_m$ [MPa]</th>
<th>$E_{mod}$ [GPa]</th>
<th>$W_e$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VECTRAN-1</td>
<td>307.49</td>
<td>1566.05</td>
<td>36.70</td>
<td>4.47</td>
</tr>
<tr>
<td>VECTRAN-2</td>
<td>276.46</td>
<td>1408.00</td>
<td>38.25</td>
<td>4.13</td>
</tr>
<tr>
<td>VECTRAN-3</td>
<td>262.33</td>
<td>1437.88</td>
<td>36.00</td>
<td>4.28</td>
</tr>
<tr>
<td>min</td>
<td>276.46</td>
<td>1408.00</td>
<td>36.00</td>
<td>4.13</td>
</tr>
<tr>
<td>max</td>
<td>307.49</td>
<td>1566.05</td>
<td>38.25</td>
<td>4.47</td>
</tr>
<tr>
<td>AM</td>
<td>260.76</td>
<td>1470.65</td>
<td>36.98</td>
<td>4.29</td>
</tr>
<tr>
<td>s</td>
<td>16.49</td>
<td>93.96</td>
<td>1.15</td>
<td>0.17</td>
</tr>
</tbody>
</table>
Calibration – What instrumentation is required

WPS1 calibration stand, which implements WPS1 calibration with a steel pin, a micrometer stage, and a CMM. The calibration procedure takes currently 1h/Sensor.

- Reference balls
- Micrometer Stage
- Steel pin
- Illumination

Steel pin, diameter = 1.58mm; LED array and an opal glass diffuser

Reference ball measurement
Calibration Procedure

1. Steel pin measured with CMM, (removing light source)
2. Calculation of pin position in mount coordinates
3. Mounting WPS1 and measuring the pin

Initial measurement of the mounting balls and reference balls allows to determine the mounting ball positions from any future reference ball positions.
### Calibration Constants

WPS1-B. We calculate the difference between the CMM and WPS measurement of wire position at $z=\pm 4$ mm. The CMM wire positions are shown in blue. The red points are the WPS measurements with their deviation from the CMM measurements exaggerated by a factor of one hundred. The rms error is 2 μm.

We determine 9 calibration constants for each camera using images of 22 wire positions. We have over twice as many wire positions as we need to fit our parameters.

<table>
<thead>
<tr>
<th>Camera</th>
<th>pivot (mm)</th>
<th>sensor (mm)</th>
<th>rot (mrad)</th>
<th>pivot- error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0195_A_1</td>
<td>-4.3892</td>
<td>88.4846</td>
<td>-4.4033</td>
<td>-13.7607</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-4.3873</td>
</tr>
<tr>
<td>P0195_A_2</td>
<td>-3.8191</td>
<td>39.3077</td>
<td>-4.6536</td>
<td>-12.7098</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-4.7217</td>
</tr>
</tbody>
</table>

Calibration constants are highly correlated; RMS value of 2μm
Images with Shadows, Showing Derivative Analysis Results. The wire is 1 mm in diameter. Its outer surface is PVC insulation.

- **Red** is the horizontal intensity profile.
- **Yellow** is the slope of the horizontal intensity profile.
- **Orange** is the fitted center-line of the wire.
- **Green** is a box to which the fitting restricts its attention.
- **Blue** is the threshold applied to the horizontal intensity profile that the analysis uses to find the approximate location of the wire.
A full scale of range test was performed at CERN, it showed the expected WPS1 range of ±5 mm. The test was performed in 0.5mm steps in the X and Z direction on the Survey CMM.

A long term test at CERN was performed and showed a standard deviation $\sigma$ was $0.87\mu m$ in X and $1.00\mu m$ for the Y position.
LWDAQ Window, Wire Image, Parameters, Results

Parameter Settings

Measurement Results

Wire Image

WPS.daq
Line Position (um): 1434.36
Line Rotation (mrad): 33.69
Number of Pixels Above Threshold in Spot: 1190
Peak Intensity in Spot: 61
Position Accuracy (um): 0.311
Threshold (counts): 6
Line Position (um): 1646.93
Line Rotation (mrad): 32.87
Number of Pixels Above Threshold in Spot: 1157
Peak Intensity in Spot: 59
Position Accuracy (um): 0.312
Threshold (counts): 6
Conclusion

Summary

- The OSI optical WPS is calibrated to better than 3 µm
- The design and concept represents a high precision low cost monitoring system

Further Implementation and Developments:

- Installation in a CLIC related test setup (TT1)
- The final version, which runs off a battery, will be arranged in sets of one hundred
- A laser will be used to transfer the DAQ results wireless
- Each measurement will take on second and will consume 30mA
- A battery will hold 10,000 mA-hr -> 1 million measurements
- Measurement once every 5 min -> 10 years of wireless operation before battery exchange

Further Information:

- http://www.opensourceinstruments.com/WPS/
- https://flackner.web.cern.ch/FLACKNER/dokuwiki/
- http://clic-alignment.web.cern.ch/clic-alignment/default.htm