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Calibration of humidity sensors for the CMS tracker

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Abstract

The calibration procedure for the HMX2000 humidity sensors that will be used in the CMS tracker is being described.

Version 1.0

1 Calibration of HMX2000 humidity sensors

As mentioned beforehand, the Hygrometrix HMX2000 piezo-resistive hygrothermal humidity sensor needs calibration before it can be used for real measurements. The calibration proceeds in two steps: calibration data are being recorded at Hygrometrix, and calibration constants are obtained from these data at CERN. In this section the procedure on how calibration constants are derived is explained and formulas how to compute from the sensor output a humidity measurement and its associated error are given.

A total of 346 humidity sensors has been bought from Hygrometrix. Sensors are being calibrated in batches, that typically consist of 40–60 sensors. Each batch has been shipped to CERN with accompanying calibration data, taken at Hygrometrix in a temperature and humidity controlled climate chamber. The sensor (a wheatstone bridge) is being excitated with a voltage of 1.25 V, and the output voltage is being recorded during the calibration as well as temperature and humidity values. The calibration data consists of recording those values for three different humidity settings (10, 20 and 30 percent relative humidity) at five different temperatures (-10, -5, 0, 5 and 10 degrees Celsius). Uncertainties on humidity and temperature are expected to be small. The sensor is believed to be linear in the temperature as well as in the humidity response. Typical calibration data (sensor output voltage as a function of humidity and temperature) are being shown in figure 1.

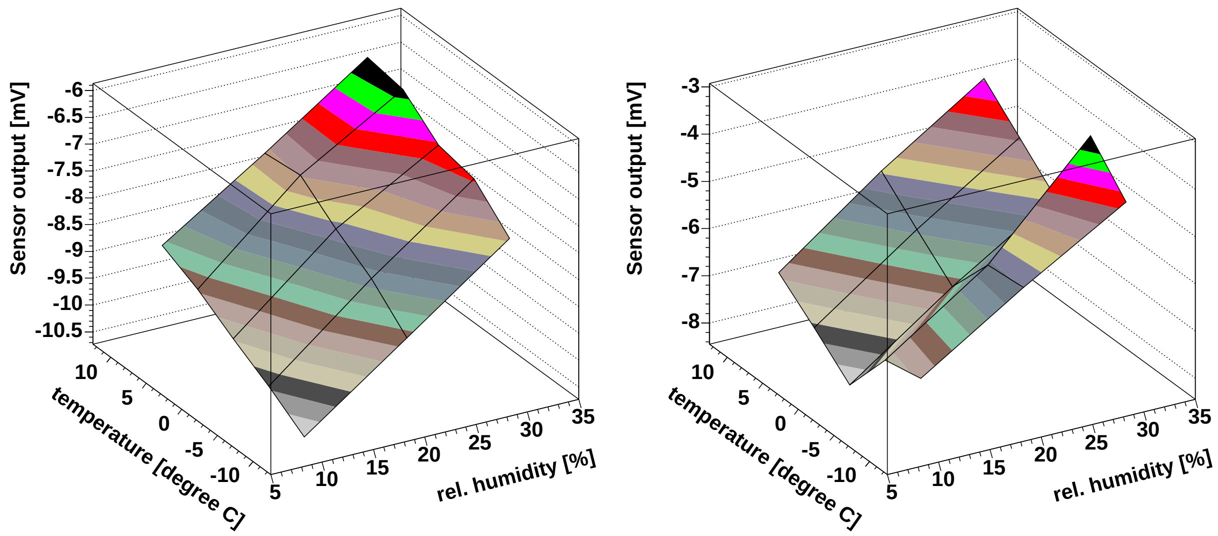

Figure 1: Calibration data as obtained from Hygrometrix. Shown is the output voltage of the humidity sensor as a function of humidity and temperature. Left: Typical calibration data of a humidity sensors. Right: Example of a bad sensor.

At CERN, these calibration data are then used to determine the parameters of the calibration plane. For each sensor, a function of the form

$$V = a + b(T - T_0) + c(H - H_0) \tag{1}$$

is being fitted to the calibration data, where a, b and c are the fitted parameters. $T_0 = 0°\mathrm{C}$ and $H_0 = 20\%$ relative humidity are being choosen to be the center of the fitted plane in order to minimize correlations between the slope parameters b and c and the offset a. In the fit, a constant error on the output voltage σ_V is being used. Errors on the measured humidity and temperature are being neglected. The size of the error σ_V is obtained by optimizing the resulting probability distribution $P(\chi^2, n)$ for $n = 15 - 3 = 12$ degrees of freedom to be most compatible with a flat distribution between zero and one. The obtained value from the fit is $\sigma_V = 0.15\,\mathrm{V}$. As can be seen in figure 2, the distribution is far from being flat, and in fact several peaks can be seen. This is a clear sign that the assumption of the correctness of the measured temperature and humidity values is not satisfied and a clear sign of systematics. In addition, the quality of the fit depends strongly on the batch in which the sensor was calibrated, which is another sign of a not yet understood systematic.

Confronted with these results, the company admitted that although the calibration procedure is carefully undertaken, the correctness of the environmental settings can not be guaranteed and may be wrongly measured, the reason being a temporary location of the calibration facility in a trailer with a low-quality climate control.

For some of the sensors, the quality of the fit is rather poor and the obtained probability low. Figure 1 compares the measurements of a sensor with a good fit quality (on the left) to the measurements of a sensor with a bad

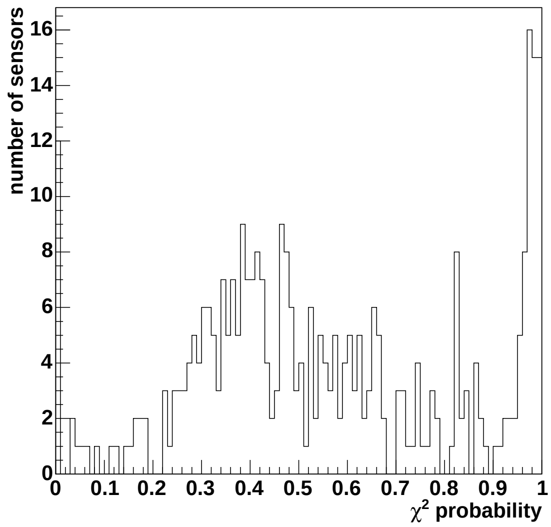

Figure 2: χ^2-Probability P of the calibration fit for 12 degrees of freedom and σ_V = 0.15 V. Sensors with $P < 0.01$ are rejected.

quality (on the right). As can clearly be seen, the behaviour of the latter is not planar but rather shows a significant structure. This was proven also for other sensors with a poor quality of the fit. As a consequence, sensors with a probability of $P < 0.01$ (cf. figure 2) are being rejected for the CMS tracker.

For all sensors where the fit quality is acceptable, the distribution of the parameters b (the temperature slope) and c (the humidity slope) are being shown in figure 3. The distribution of the temperature slope can be nicely described by a gaussian destribution with a mean of $\mu = 0.09$ mV/K and $\sigma = 0.014$ mV/K. In contrary, the distribution of the humidity slope shows two distinct peaks and does not represent a gaussian distribution. The mean of the distribution is 0.15 mV/%RH with a RMS of 0.013 mV/%RH. Hygrometrix reports for their sensors a typical humidity slope of 0.18 mV/%RH for an excitation voltage of 1.5 V, which scales well with the 0.15 mV/%RH for 1.25V excitation voltage used for CMS. One sensor shows almost zero slope for changes in humidity and temperature and was found to produce no output at all. It was therefore rejected for the CMS tracker. In total, 346 sensors have been calibrated in this procedure.

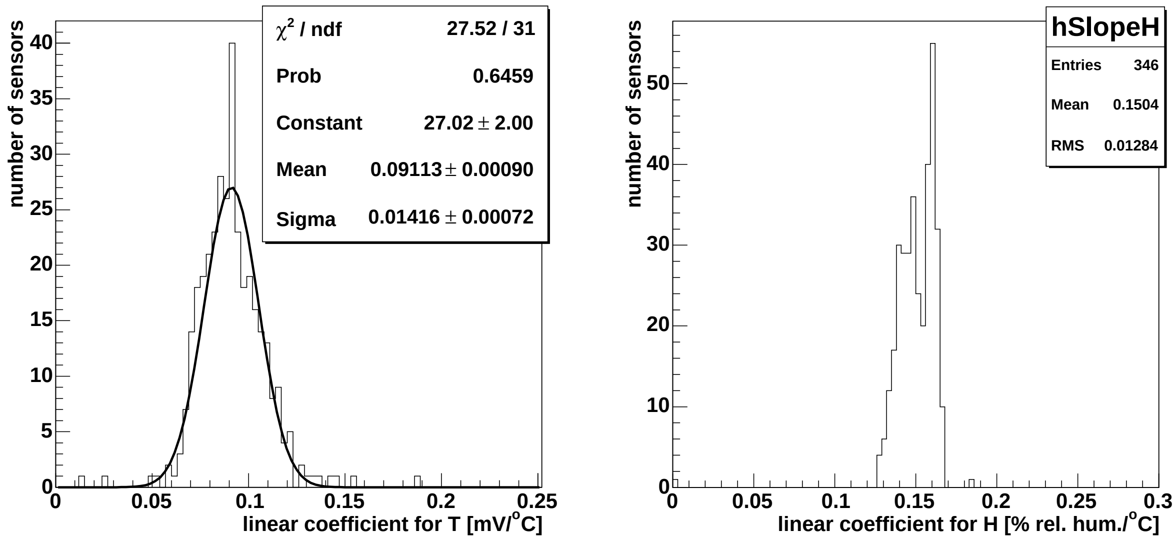

Figure 3: Distribution of the fitted slope parameters. Left: Temperature slope. Right: Humidity slope.

2 Measuring Humidity in CMS

The output voltage of the humidity sensors is converted in a current in the range from 4 mA to 20 mA with help of a special conditioning circuit which is fed into a PLC that is part of the general CMS Detector Control System (DCS). Since the design of this circuit is not yet known, the following formula only apply to a measurement of the output voltage V of the sensors.

The above formula (1) for the calibration plane can be solved for the humidity easily:

$$H = H_0 + (V - a - b(T - T_0))/c \tag{2}$$

The parameters H_0 and T_0 are fixed and taken from the calibration procedure. The parameters a, b and c are determined through the fit and vary for each sensor. To measure the humidity, a measurement of both the sensor output voltage V and the temperature T is necessary. The latter can be obtained from temperature sensors that are as close as possible to the humidity sensor.

To determine the precision of the measurement, additional information is necessary. Assuming that the voltage measurement is independent from the temperature measurement and both are independent of the calibration procedure described above, one obtains from equation (2) with error propagation

$$\delta H^2 = (\delta V^2 + (b\delta T)^2)/c^2 + J^T \cdot C \cdot J \tag{3}$$

where J is the Jacobian matrix of derivatives

$$J = \begin{pmatrix} \partial H/\partial a \\ \partial H/\partial b \\ \partial H/\partial c \end{pmatrix} = \frac{1}{c} \begin{pmatrix} -1 \\ -(T - T_0) \\ b(T - T_0) \end{pmatrix} \tag{4}$$

and C is the correlation matrix obtained from the fit in the calibration. Typical values of the off-diagonal correlation coefficients are 4-7%.

It is interesting to see the size of the error as a function of temperature (it is not a function of the humidity). This can be visualized in the following way: In figure 4, the mean and variance of the error on the humidity measurement of all sensors is shown as a function of the temperature T in the range from -25° C to 25° C. The error on the output voltage has been set to 0.17 mV and the error on the temperature has been set to 1°C. From equations 3 and 4 one expects a second order polynom. The absolute error on the relative humidity ranges from 1.3% to 1.7%, dominated by the error on the output voltage measurement. From the humidity slope shown in figure 3 one can easily see that a change in voltage by 0.15 mV corresponds to a change in humidity of 1%. Whether the above error estimate on the output voltage measurement of 0.17 mV is realistic one has to decide after the design of the conditioning circuit.

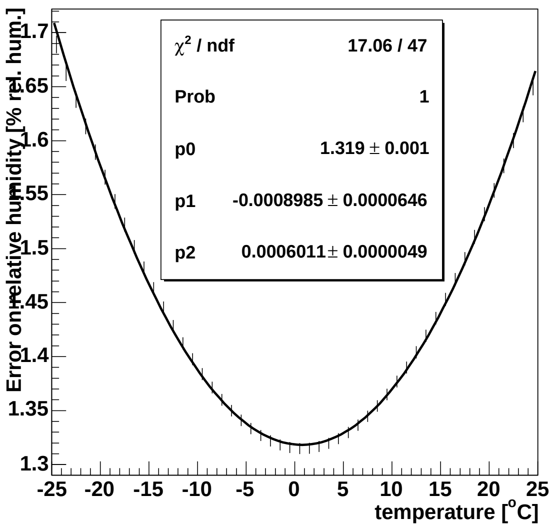

Figure 4: Error on the relative humidity as a function of the temperature T.

3 Storing calibration data in the Tracker Construction Database

To summarize the ingredients necessary for the humidity measurement in the CMS tracker, the calibration constants and the correlation matrix need to be known. It was choosen to store those parameters, marked with the sensor ID, in the Tracker Construction Database (TrackerDB) [1].
In the Tracker Outer Barrel, humidity sensors are mounted only of rods of type x.x.1 (according to TrackerDB type convention), i. e. rods with a CCU with address 1 which are at the start of each control loop. Storing parameters about a component in the TrackerDB requires the component to have been defined as a database object, i.e. to be identified in the DB by an object ID (usually, a barcode number). This is not the case for humidity sensors, which have not been defined as objects. Thus, it was decided to consider them, for database purposes, as a feature of rods of type x.x.1 (which instead are defined as objects). Parameters are inserted into an action table (i. e. a DB table which contains data coming from component testing) called `HUMSENCAL` pertaining to the rod. To ease data insertion, a refined version of the Rod Assembly plugin for the BigBrowser program is used [2]. Figure 5 shows a screen shot of the Rod Assembly plugin asking the user for the sensor ID. The calibration values are obtained from a file that is stored locally on the computer and created during the calibration procedure.

The plugin guided procedure provides a safer way for assembly operators to avoid mistakes in inserting data (e.g., a humidity sensor can't be mounted on a rod which is not of the correct type, and it will always have to be mounted on a x.x.1 rod to be able to go on in the assembly process).

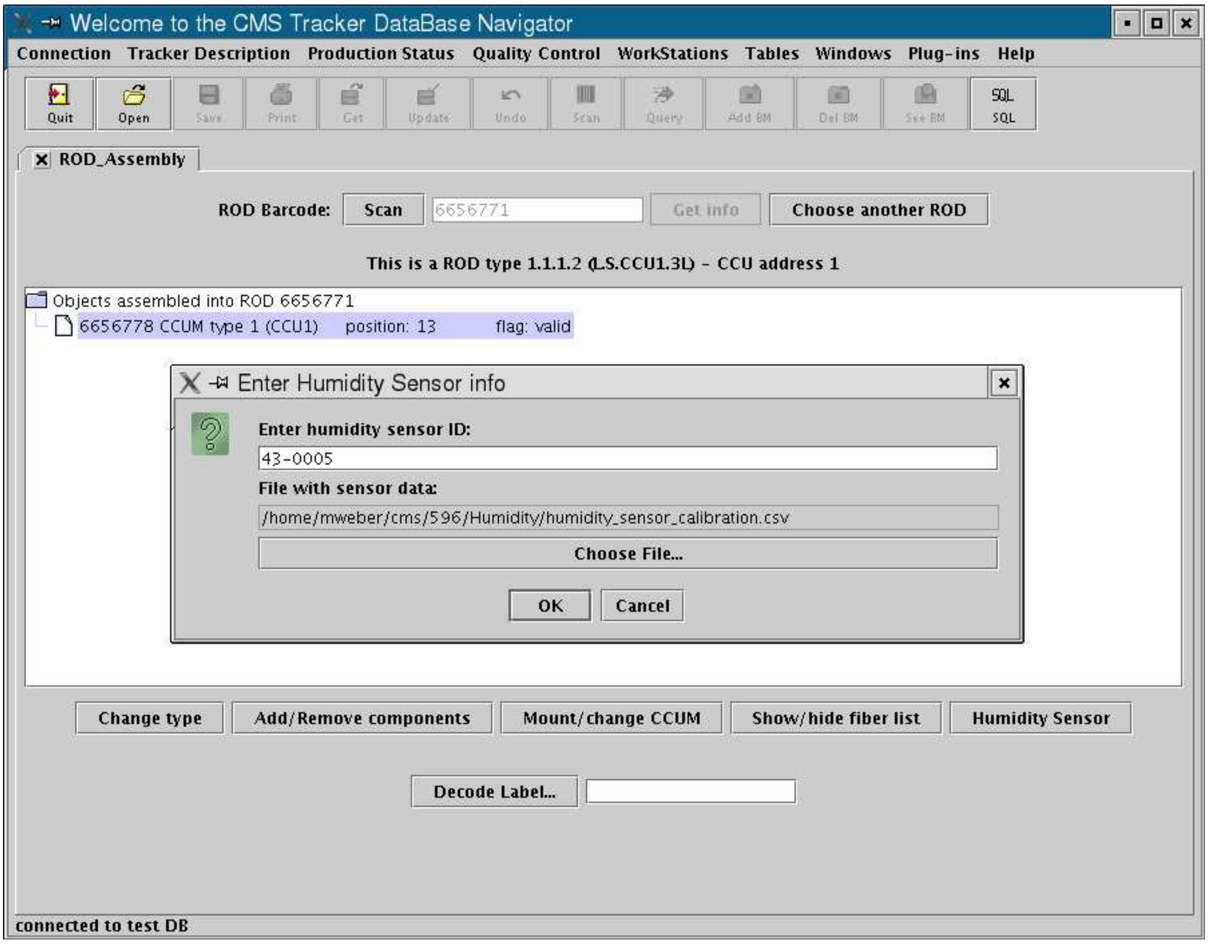

Figure 5: Rod assembly plugin. The humidity sensor ID has to be entered for all rods of type x.x.1 and the calibration data are stored in the Tracker Construction Database.

4 Conclusion

346 HMX 2000 humidity sensors have been calibrated. During the calibration process, 13 sensors showed not satisfactory performance and have been rejected to be used in the CMS tracker. Calibration data to determine the humidity in the CMS tracker has been computed and stored in a file.

During assembly of a rod, the calibration information is being read from a file and inserted into the Tracker Construction Database by the Rod Assembly plugin for the BigBrowser program.

During operation of CMS, the information can be retrieved from the TrackerDB and with existing C++ code the humidity and its associated error can be computed.

References

[1] **CMS Tracker Database Browser homepage**, in *http://cmsdoc.cern.ch/~cmstrkdb/*

[2] **Rod Assembly plugin**, M. Risoldi, in *http://duccio.home.cern.ch/duccio/cms/TOB/DB_model/ROD/index.htm*