TECH NOTE #007:: Highly accurate and dynamic temperature measurement with thermocouples (full thermally calibrated measurement chain)

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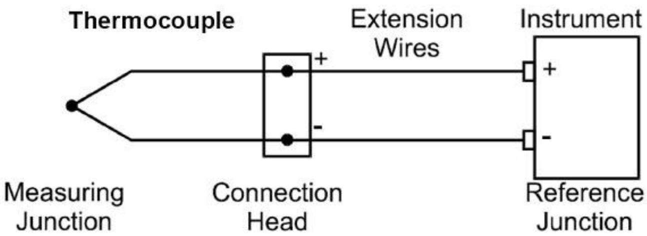
Abstract

This Tech Note describes typical requirements and its solution for highly accurate and dynamic temperature measurement using thermocouples in research and development and state off the art measurement technology from HBM achieving a temperature measurement accuracy down to +/- 0,5 K.

Temperature Measurement with Thermocouples

Temperature still is the most often measured physical process parameter in industry. Temperature measurement utilizes many different forms of sensors: thermocouples (**TC**), Resistance Temperature Detectors (**RTD**, for example platinum based sensors like Pt100 with 100 Ohm or Pt1000 with 1000 Ohm), thermistors (**NTC, PTC**) or integrated circuit temperature sensors (**KTY**) – just to name the most common technologies. In research and development, industrial applications and in general remote sensing, thermocouples and RTD's are the most popular sensor types in use.

A thermocouple produces a small voltage created by the junction of two different metals, when the temperature difference between one end of a conductor and the other end that produces a small electromotive force (EMF) or charge imbalance, that leads us to the temperature difference across the conductor.



Temperature changes in the wiring between input and output will not affect the output voltage, provided all wires are made of the same material as the thermocouple.

Different conductive metals will produce different levels of EMF or charge separation relative to the thermal gradient across the metal. Thomas Seebeck discovered this principle in 1822 and it is known today as the Seebeck Effect‖.

The common types of TCs include **J, K, N, T, E, R, S, B** and **C** which refer to the two types of different material they are constructed of. The ranges for all types of thermocouples can be found in NIST (National Institute of Standards and Technology) reference tables at www.nist.gov. All types have their advantages for certain applications, ambient conditions and also their specific history and evolution in different markets and application. Type K and N for example are used in high numbers in automotive industry.

The common TCs used in industry are based on Nickel alloy. Characteristic functions for thermocouples that reach intermediate temperatures, as covered by nickel alloy thermocouple types E, J, K, M, N, T.

Type E (chrome–constantan) has a high output (68 µV/°C) which makes it well suited to cryogenic use. Additionally, it is non-magnetic. Wide range is −50 °C to +740 °C and Narrow range is −110 °C to +140 °C.

Type J (iron–constantan) has a more restricted range than type K (−40 °C to +750 °C), but higher sensitivity of about 50 µV/°C. The Curie point of the iron (770 °C)[9] causes a smooth change in the characteristic, which determines the upper temperature limit. The Type J is a popular thermocouple that is commonly used to monitor temperatures of inert materials and in vacuum applications – also in hot processes including plastics and resin manufacture. This thermocouple is susceptible to oxidisation so is not recommended for damp conditions or low temperature monitoring. Note that the accuracy of this sensor may be permanently impaired if used above 760°C.

Type K (chromel–alumel) is the most common general purpose thermocouple with a sensitivity of approximately 41 µV/°C (chromel positive relative to alumel when the junction temperature is higher than the reference temperature). It is inexpensive, and a wide variety of probes are available in its −200 °C to +1350 °C / -330 °F to +2460 °F range. Type K was specified at a time when metallurgy was less advanced than it is today, and consequently characteristics may vary considerably between samples. One of the constituent metals, nickel, is magnetic; a characteristic of thermocouples made with magnetic material is that they undergo a deviation in output when the material reaches its Curie point; this occurs for type K thermocouples at around 350 °C.

Type N (Nicrosil–Nisil) thermocouples are suitable for use between −270 °C and +1300 °C owing to its stability and oxidation resistance. Sensitivity is about 39 µV/°C at 900 °C, slightly lower compared to type K. Type N has been designed as successor of type K but never achieved it due to the strong distribution of type K, huge amount of available sensors, existing data acquisition solutions and established colour code.

Designed at the Defence Science and Technology Organisation (DSTO) of Australia, by Noel A. Burley, type N thermocouples overcome the three principal characteristic types and causes of thermoelectric instability in the standard basemetal thermo element materials:

1. A gradual and generally cumulative drift in thermal EMF on long exposure at elevated temperatures. This is observed in all base-metal thermo element materials and is mainly due to compositional changes caused by oxidation, carburization, or neutron irradiation that can produce transmutation in nuclear reactor environments. In the case of type K thermocouples, manganese and aluminium atoms from the KN (negative) wire migrate to the KP (positive) wire, resulting in a down-scale drift due to chemical contamination. This effect is cumulative and irreversible.
2. A short-term cyclic change in thermal EMF on heating in the temperature range ca. 250–650 °C, which occurs in types K, J, T, and E thermocouples. This kind of EMF instability is associated with structural changes such as magnetic short range order in the metallurgical composition.
3. A time-independent perturbation in thermal EMF in specific temperature ranges. This is due to compositiondependent magnetic transformations that perturb the thermal EMFs in type K thermocouples in the range ca. 25-225 °C, and in type J above 730 °C.

The Nicrosil and Nisil thermocouple alloys show greatly enhanced thermoelectric stability relative to the other standard base-metal thermocouple alloys, because their compositions substantially reduces the thermoelectric instabilities described above. This is achieved primarily by increasing component solute concentrations (chromium and silicon) in a base of nickel above those required to cause a transition from internal to external modes of oxidation, and by selecting solutes (silicon and magnesium) that preferentially oxidize to form a diffusion-barrier, and hence oxidationinhibiting films.

Type N is used for temperature

- profiling in ovens, furnaces and kilns
- measurement of gas turbine and engine exhausts
- Monitoring throughout production and smelting process in the steel, iron and aluminium industry

Type T (copper–constantan) thermocouples are suited for measurements in the −200 to 350 °C range. Often used as a differential measurement since only copper wire touches the probes. Since both conductors are non-magnetic, there is no Curie point and thus no abrupt change in characteristics. Type T thermocouples have a sensitivity of about 43 µV/°C. Note that copper has a much higher thermal conductivity than the alloys used in thermocouple constructions, and so it is necessary to exercise extra care with thermally anchoring type T thermocouples.

Type T is used widely in food industry, mainly due to the high level of accuracy it provides and because it performs well in the presence of moisture without oxidising to identify potential food safety hazards and complies with HACCP regulations. If in general a lower range temperature measurement and cryogenic applications is required, Type T is a popular choice too.

Reference Junction: The point where the TC enters the measurement system will itself act as a thermocouple – normally TC material to copper. This affect can be minimized by making sure the connections are at the same temperature. This is not easy as small thermal gradients will usually occur, often as a result of the self-heating of components across the circuit board or by varying ambient temperature. In case the temperature of the (cold) junction is measured highly precise on this spot this can be taken to compensate the thermoelectric contribution of the cold junction (for QuantumX it is PT1000 between every second thermo mini connector. All sockets are close to each other). The Type K thermocouples use the magnetic material Nickel. Magnetic materials will exhibit a step change in their output once they reach their Curie point, which for a Type K occurs at approximately 354 °C. The Curie point refers to the temperature where a ferromagnetic material becomes paramagnetic when heated. For example, a magnet will lose its magnetism if heated above the Curie temperature. This is a reversible change on cooling for Nickel.

Thermocouples – Advantage and Challenge

Thermocouples have some significant advantageous and are widely used in many industrial fields:

- Wide temperature range: -200 … 1750 °C (-328 … 3182°F)
- Fast response time (down to 0.10 seconds)
- Small size (fitting into smallest gaps)
- No lead resistance effects
- Low cost
- Self-powered
- No self-heating
- extremely rugged / work in harsh environment (shock, vibration, corrosive environments, …)
- long distance from measurement spot to device

But thermocouples also have some disadvantageous:

- (Cold) junction reference needed for compensation
- Low accuracy (1 … 5 K) and high variance when multiple different patches are in use
- Non-linear
- Stability
- TC extension leads needed

Since accuracy plays a significant role in selecting a sensor type, we have to be familiar with potential sources of error when making temperature measurements with thermocouples. Some of these considerations may lead directly to another sensor type like RTD. Some manufacturers of thermocouple sensors offer better than standard performance.

One important property of thermocouples is their non-linearity. The output voltage is not linear over measured temperature. The measurement device needs to run a mathematical linearization converting TC output voltage to temperature accurately.

By the IEC 584-2 standard, thermocouple sensors are divided into three accuracy classes: Class 1, Class 2, and Class 3. By this standard, two tolerance values apply for a given temperature and thermocouple type: a fixed value and a calculated value based on the sensor temperature. The larger of these two values is normally taken as the sensor tolerance.

For thermocouples type K Class 1 we have:

Temperature range	Tolerance Class 1 (°C)	Tolerance Class 2 (°C)
-180 … 1300 °C	± 1.5 between -40… 375°C ± 0.004 x T between 375 … 1000 °C	± 2.5 between -40… 333°C ± 0.0075 x T between 333 … 1200 °C

Tolerances result of varying production process of NiCr and NiAl alloys.

The accuracy of thermocouples is not high. Even with Class 1 TCs.

QuantumX General Overview

QuantumX is a modular distributable data acquisition solution from HBM for measurement and testing solving demanding engineering tasks for quicker innovation. The data acquisition modules offer highly accurate inputs acquiring physical quantities in the wide field of **mechanical, hydraulics, thermal** and **electrical or mixed systems** with data rates from 0.1 to 100 kS/sec per channel. QuantumX acquires sensor or transducer inputs measuring **force, strain, torque, pressure, temperature, displacement, speed, position, acceleration, flow, voltage, current** and many more. QuantumX offers superb A/D inputs supporting **voltage, current, bridge based inputs for strain gage or inductive transducers, LVDT, resistive** and **thermocouple**. In addition to that **digital pulses** from or **digital signals** acquired from field busses like **CAN bus**. All inputs are acquired fully parallel and time synchronous.

Some modules offer real-time capability:

- Calculation: PID control, limit switch, matrix calculation, addition, multiplication, and more
- Gateway: simply routing any signal (analog, digital or calculated signal) to: analog output, CAN bus, EtherCAT
- Signal Generator: starting and stopping a predefined signal generator or replay an acquired signal

QuantumX MX1609 Thermocouple Amplifier

MX16**09K**B and MX16**09T**B have been designed together with measurement experts getting a product which combines all advantages of a thermocouple-based measurement and the target to achieve highest accuracy close to RTD based measurement. The letters 09 stand for thermocouple at HBM. MX1609KB supports thermocouple type K, MX1609TB supports type T on all 16 channels.

Every input supports

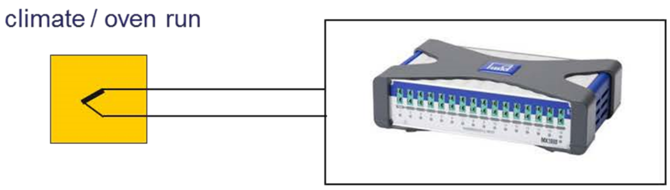
- socket or channel individual “cold” junction compensation with high resolution PT1000 temperature measurement
- integrated IEC conform polynomial scaling curve (electrical → temperature)
- second user specific additional scaling based on a thermal calibration run (2…10 points over range) can be stored even in the thermocouple plug from HBM (RFID technology)
- Automatic channel naming based on RFID technology can be used to
    - name the measurement spot (examples: e-drive-TCK, inverter-IGBT1, e-drive-stator-1) which makes it a plug and play system and allows set ups in seconds
    - Reference or calibration points can be stored using thermal calibration charts
- Configurable data rates up to 300 Hz per channel and bandwidth up to 15 Hz for high dynamic applications like brake vehicle testing
- full galvanic isolation makes integration easier, allowing highly accurate measurement without floating mass
- extendible system concept with any module and input of the QuantumX series • channel to channel and module to module time synchronization

All QuantumX modules are compact units and based on Ethernet technology.

QuantumX Thermal Calibration

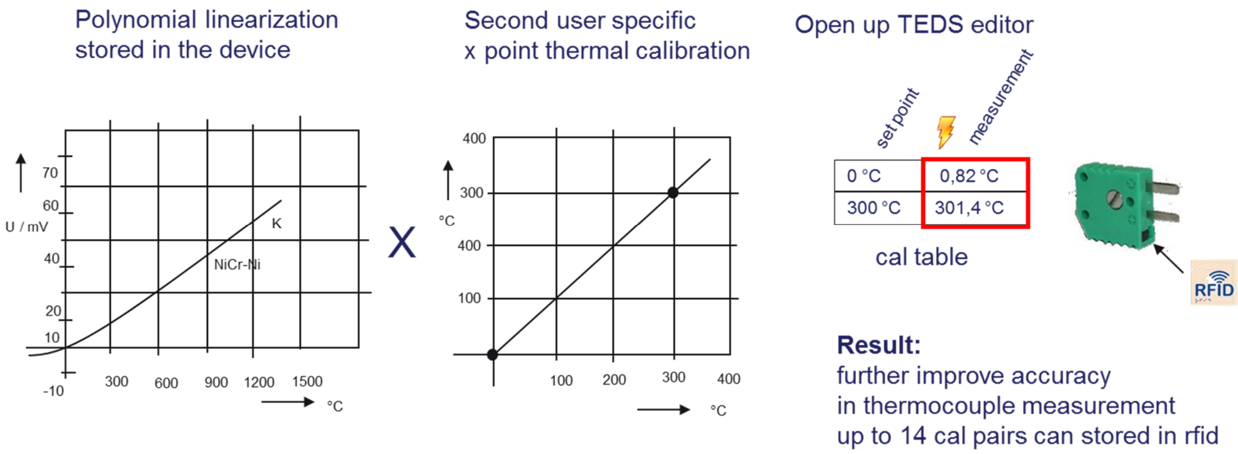
Still accuracy in terms of temperature measurement is a relevant factor and many companies want to keep the benefits of temperature measurement with thermocouple and ask for an overall true temperature accuracy of +/- 0.5 K.

With QuantumX there is a chance to further improve accuracy for thermocouple measurement.



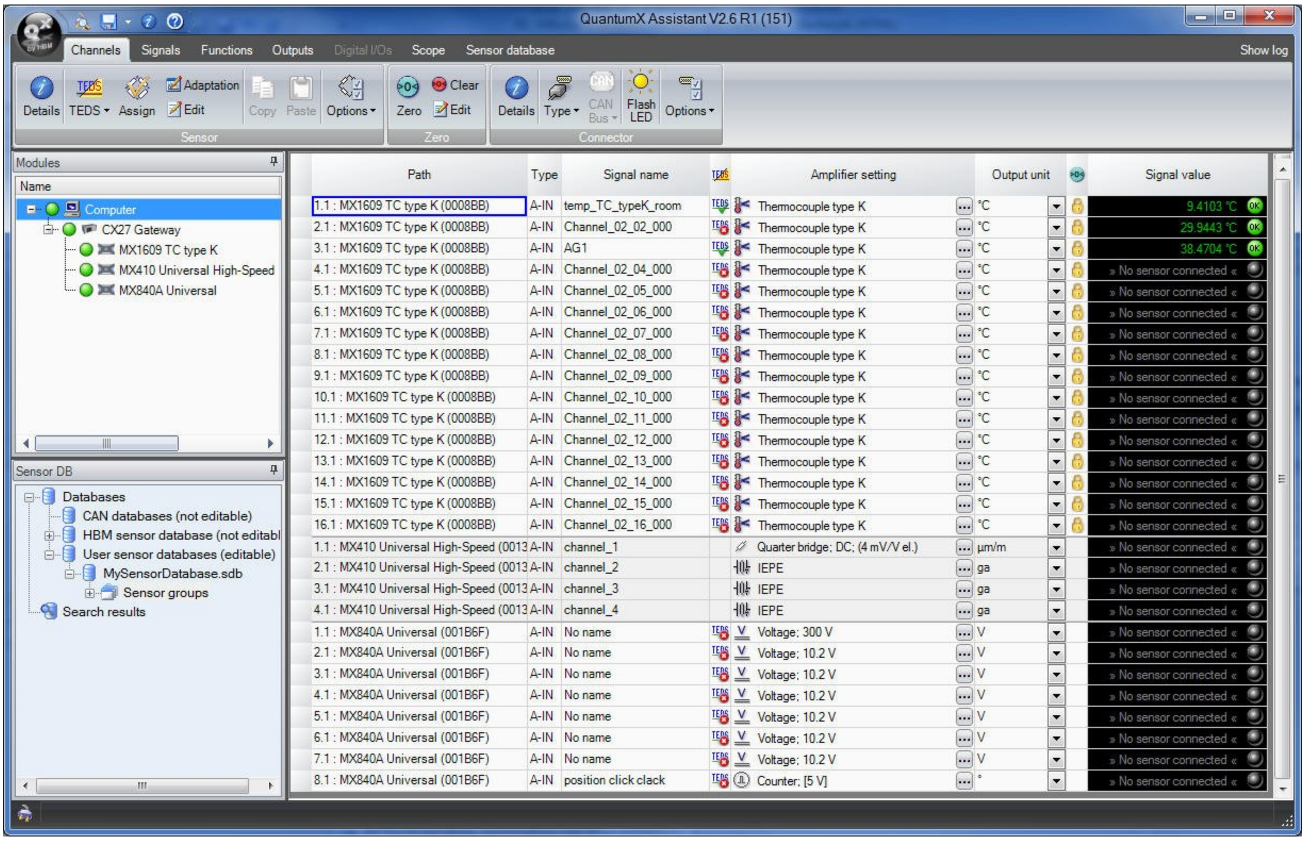
QuantumX MX1609KB amplifier offers 16 channel thermocouple inputs and linearizes the mV input from TCs according to an IEC polynomial curve. A second multi-point linearization can be stored on the RFID located in the thermo mini plug or in the sensor database. For this measurement it is OK doing a 2-point thermal calibration of one TC out of the same set of sensors - first set point in ice water with 0°C and second set point for example with 300 °C. The effect is that measurement accuracy can be improved dramatically down to an overall ± 0.5 K.

A maximum of 14 pairs can be used for this second user specific thermal calibration.

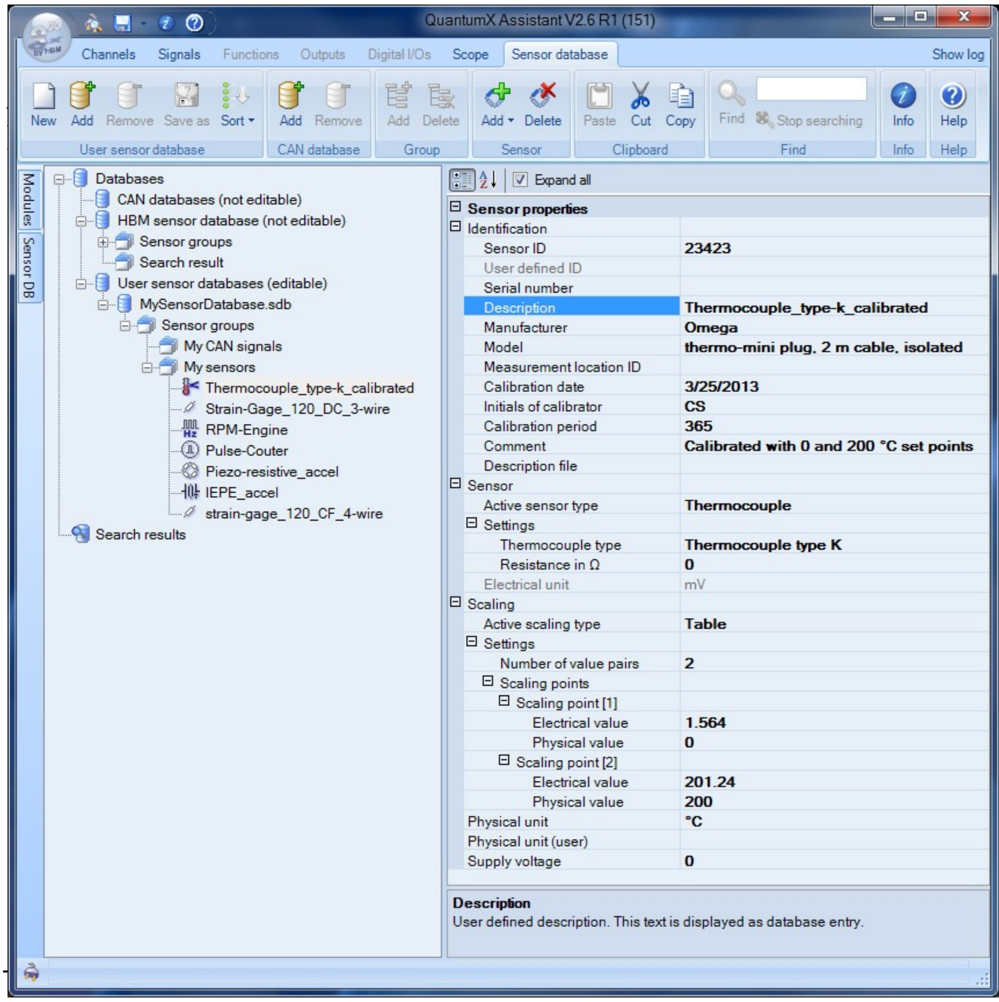


QuantumX – Calibrating the complete measurement chain

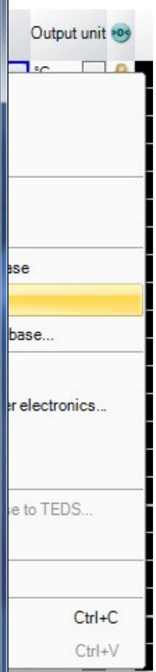
MX Assistant is a for free tool which enables overall parameterization of the DAQ system and parameterize the channels. MX Assistant is available in English, Japanese, German and French language.



In case you do not use the thermo mini plug from HBM with integrated RFID chip you enter the thermocouple sensor into the sensor database in the MX Assistant.

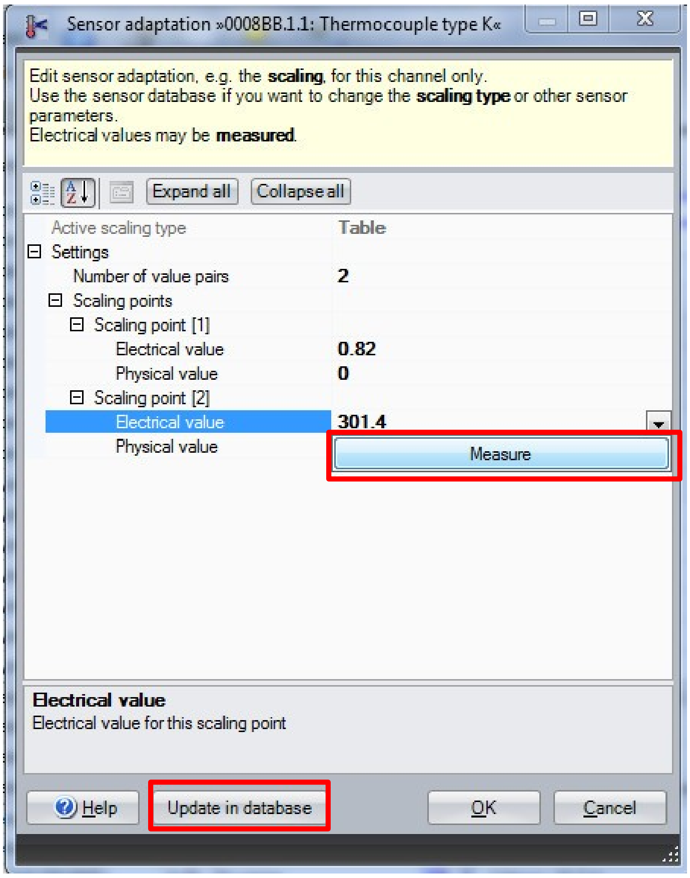


atabase to the channel
the column “Amplifier



wing dialogue.

Enter your set points and measure in your true measured temperature. Then store this permanently in the sensor database – Update in database.



In case you work with the **thermo mini plugs including RFID chips** from HBM (1-THERMO-MINI or 1-THERMO-MINI-T) you can store the calibration data permanently to the chip located in the plug which basically allows you plug & measure. Adapt the sensor scaling with right mouse click in the column “Amplifier settings” and select “Edit adaption…”.

Conclusion

A two-step thermally calibrated measurement allows you to boost measurement accuracy significantly.

We would recommend the following measurement chain:

- same batch of class 1 thermocouples
- thermo mini plug from HBM with RFID / TEDS which allows you to store all cal data in the thermocouple
- QuantumX MX1609 thermocouple measurement module
- catman Easy for sensor calibration and storing the data permanently

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