The Millikelvin Challenge—Cryogenic Control with Industrial PLCs

Roland Reiss, Sebastian Deiries

European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany

ABSTRACT

The precise and reliable control of detector temperature and monitoring of detector vessel vacuum pressure is essential for the operation of optical and infrared imagers. We present the design of a cryogenic controller based on an industrial PLC (Programmable Logic Controller). The controller not only controls detector temperature but keeps care of a continuous flow crystat where the cold plate temperature is stabilized through the LN2 flow.

The cryogenic controller supports various types of thermal sensors, like Si diodes, PT100 and Cernox(tm) RTDs. The PLC I/O terminals have been selected to achieve a very high resolution and accuracy of the temperature measurement and control. The calibration of the Si diode and Cernox(tm) sensors is done by the PLC software using vendor provided calibration coefficients. The thermal resolution is better than 1 mK, control stability is in the range of a few millikelvins, absolute accuracy is only limited by the vendor calibration. The monitoring of vacuum pressure, numerous interlocks, softstart and setpoint ramping guarantee a safe operation.

INTRODUCTION

We have designed a prototype Cryogenic Controller (CC) based on Programmable Logic Control (PLC) to thermally control a Detector Head (DH) cooled by a Continuous Flow Cryostat (CFC). DH and CFC are widely used at ESO, i.e. for the MUSE instrument [1]. The PLC serves three main thermal control loops, — Detector (DTR), Cold Plate (CPL), and Exhaust Gas (EXG) temperatures. A fourth loop is needed for the Sorption Pump (SPT) regeneration heater. DTR, EXG and SPT temperatures are maintained by heater resistors, while the CPL cooling is controlled by an electromagnetic valve regulating the LN2 flow. The CPL temperature is typically kept ~45K below the DTR temperature.

In addition to thermal control the CC must also monitor vacuum pressure for safety reasons. An interlocking system prevents cooling in case of poor vacuum.

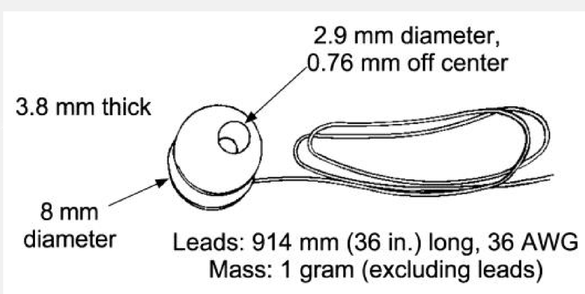
DESIGN GOALS

- High temperature resolution (<1mK)
- High control stability (~1mK RMS)
- Graphical user interface
- Use of COTS components
- Integration into ESO VLT SW environment
- Fail-safe operation

TEMPERATURE SENSORS

The CC supports different temperature sensors:

- **PT100 RTDs**
- **DT-670 Si diodes** (LakeShore)
- **Cernox resistors** (LakeShore)



PT100 are a widely used industry standard but suffer from a limited low temperature range. Cernox RTDs have an excellent performance at low temperature (sensitivity) and they work down to ~1K. The chosen type (CX-1080-CU-HT-20L) has an electrical resistance range of approx. 150Ω..8kΩ between 300K and 20K.

VACUUM SENSORS

Vacuum monitoring is done with an Edwards Wide Range Gauge (WRG). The WRGs have an analog output of 2..10V corresponding to a range of 10^{-12} to 10^{3} mBar.

GAS COUNTER

To monitor LN2 consumption we are using natural gas flow counters from Elster-Instromet[2] with an M-bus or **Meter-Bus (European Standard EN 13757)**[3] interface to measure the N2 exhaust gas volume.

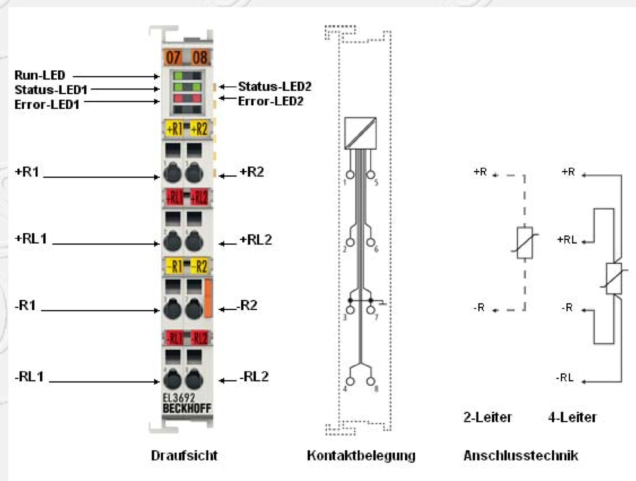
HEATERS, VALVES, INTERLOCKS AND ALARMS

Heater resistors and LN2 valve are interfaced by digital output modules with 24V/4A drive capability. Alarm signals to ESO's Central Alarm System (CAS) are available on two relay outputs. External interlock signals (i.e. to sense a connected vessel) are interfaced by digital input modules.

PLC HARDWARE

We have chosen a **Beckhoff PLC** with **EtherCAT field bus** components[4] to interface with the above mentioned sensors and actuators:

- **CP6207** embedded PC, 6 inch touch panel display, WinCE6, Atom 1.1GHz CPU, 1GB RAM
- **EK1100** bus coupler
- **EL1008** 8x digital input
- **EL3202**-0010 2 channel analog input for PT100, high precision
- **EL3602** 2-channel analog input +/-10V differential, 24 bit for DT-670 and Edwards WRG
- **EL3692** 2-channel 4-wire resistance measurement for Cernox resistors
- **EL2042** 2-channel digital output 24V, 4A for heater and valve control



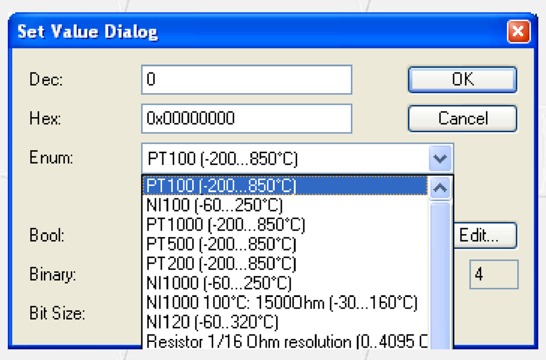
- **EL2622** 2-channel relay output for CAS
- **BK1250** Coupler between E-bus and K-bus
- **KL6781** M-bus interface for natural gas counter

PLC SOFTWARE

We are using the Beckhoff **TwinCAT 2** software development system[5]. TwinCAT is compliant with **IEC 61131-3**. The interface to the VLT software is realised through the **OPC-UA** cross platform framework[6].

SENSOR RESOLUTION

For PT100 sensors the resolution is limited by the EL3202-0010 terminal to 10mK. The terminal delivers a linearized integer value in 1/100°C. The EL3202 supports also a wide range of RTDs, i.e. PT200 to PT1000 as well as KTY81 variants. However, a resolution of 10mK is not enough to stabilize a temperature to a few mK.



A much better choice for high sensitivity at low temperatures are the LakeShore Cernox RTD sensors . The selected CX-1080-CU-HT-20L has a dR/dT of -3Ω/K at 165K and -18 Ω/K at 77K. At room temperature (300K) the dR/dT drops to -0.75Ω/K. Considering the resolution of ~1mΩ in the 1..10kΩ range provided by the EL3692 terminal the resolution is **~0.3mK at 165K and ~50µK at 77K!**

POLYNOMIAL EQUATION

Calibration Report: 723917	Sales Order: 80308
Sensor Model: CX-1080-CU-HT-20L	Serial Number: X79251
Sensor Type: Cernox Resistor	Temperature Range: 20.0K to 325K

Polynomial Type: Chebychev

Useful Range of Fit:

95.1 K to 325. K

903.4 Ohms to 164.3 Ohms

Lower and Upper limits of Log(Resistance) used in computing Chebychev coefficients:

ZL = 2.2061546907 ZU = 3.02164047088

Order	Coefficient	Std. Deviation of Coefficient	Ratio (Coeff./Std Dev.)
0	187.359795	7.6934E-04	243533.90
1	-119.900374	1.1800E-03	-101608.09
2	19.912607	1.1140E-03	17875.26
3	-2.617973	1.1157E-03	-2346.45
4	0.405452	1.0799E-03	375.45
5	-0.064344	1.0302E-03	-62.46
6	0.008549	1.0113E-03	8.45
7	-0.004225	1.0228E-03	-4.13
8	0.001459	1.0072E-03	1.45

Z = Log(Resistance)

k = ((Z-ZL)-(ZU-Z))/(ZU-ZL)

Temp. (K) = ΣA$_i$* COS(i * ARCCOS(k)), where 0 <= i <= 8 and the A$_i$'s are the coefficients in the table above.

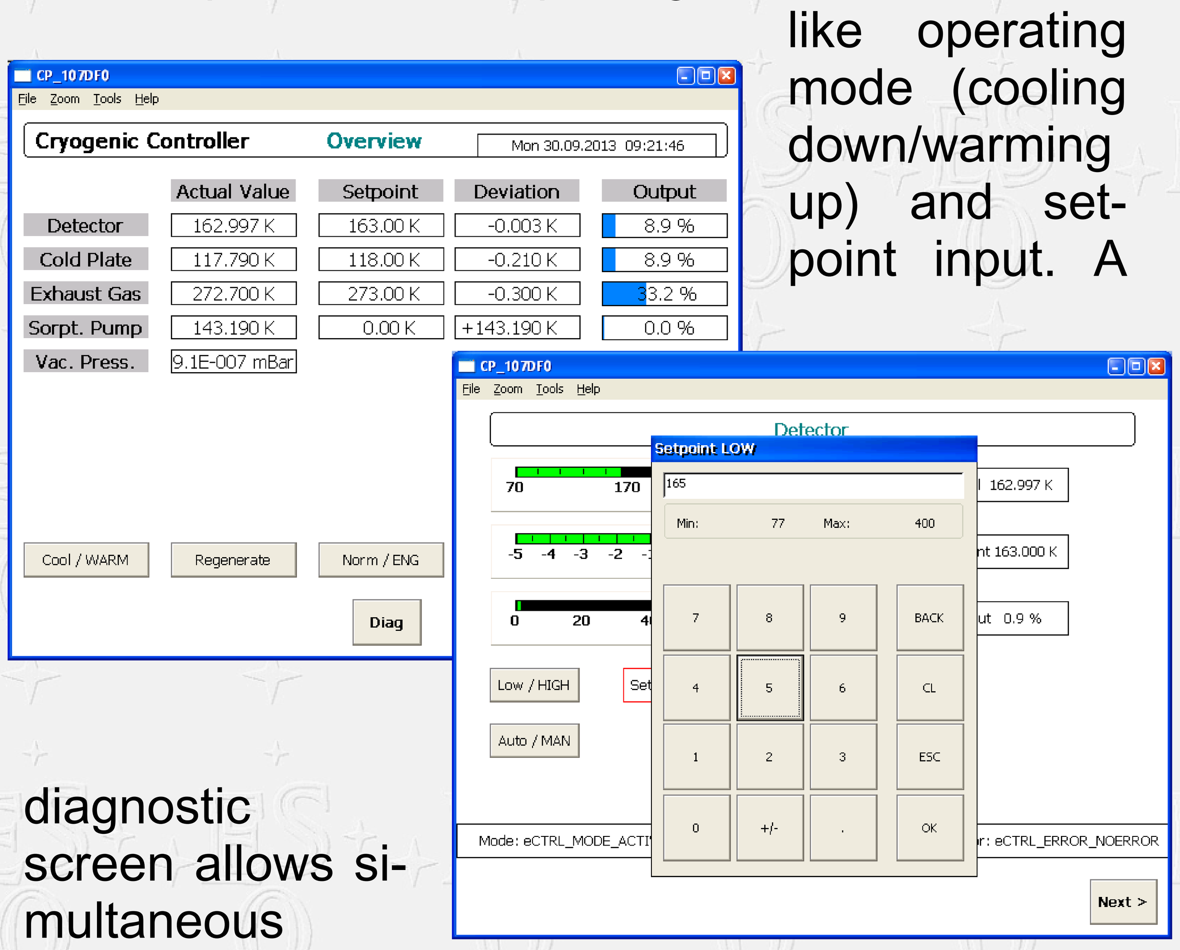
The linearization and calibration of the Cernox sensors is done with a “Functional Block” (FB) routine written in “Structured Text” (ST) and uses the **Chebychev calibration coefficients** provided by LakeShore. The same FB with generic coefficients is used to calibrate the DT-670 diode. Performance of the DT-670 was disappointing due to very noisy response.

PID CONTROL

The four Proportional-Integral-Derivative (PID) control loops (per vessel) are implemented with the Beckhoff TwinCAT PLC Temperature Controller library. This library offers **closed loop (automatic)** and **open loop (manual)** control as well as **soft start** and **setpoint ramping** options.

GRAPHICAL USER INTERFACE (GUI)

A simple GUI for touch screen operation has been implemented supporting the basic functions like operating mode (cooling down/warming up) and setpoint input. A diagnostic screen allows simultaneous comparison of the different thermal sensors.



CONCLUSION

The PLC based Cryogenic Controller prototype has shown very promising results. The **resolution** of the temperature measurement is far better than **1mK**, the **accuracy** only depends on the calibration of the sensors and is typically in the range of **a few mK**. **Control stability** is in the range of **5mK peak-to-peak**.

REFERENCES

[1]Lizon, J. L. et al., “Vacuum and Cryogenic System for the MUSE detectors”, Proc. SPIE 8446-217

[2]Elster-Instromet, http://www.elster-instromet.com/en/index.html?changelang=1

[3]Meter-Bus, http://en.wikipedia.org/wiki/Meter-Bus

[4]Beckhoff Information System, http://infosys.beckhoff.com/index_en.htm

[5]Beckhoff TwinCAT2, http://www.beckhoff.de/english.asp?twincat/

[6]OPC Foundation, https://www.opcfoundation.org/Default.aspx