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Measurement and control architecture of research cryostats

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At ZEA-1 we develop, build and operate, among other things, cryostats for scientific applications to liquefy gases such as hydrogen, e.g. with variable ortho para content for the moderation of neutrons. Further areas of application include Raman spectroscopy and particle image velocimetry (PIV) with cryogenic liquids, testing and calibration of sensors and actuators at cryogenic temperatures and freezing of fluids to grow crystals at cryogenic temperatures.
Following the guiding principle of reliability, modularity and open source, the sensor and actuator networking as well as the measurement and control architecture of our research cryostats have been fundamentally rethought. The control logic of the cryostat, the measurement analysis, the calculation and storage of the data, the human-machine interface as well as the visualization of the measurement and machine data were largely virtualized using containers. The required hardware has been reduced to a minimum and connected to the virtual environment via an encrypted data line, regardless of whether the connection uses the 5G standard, WLAN or LAN. The safety of the cryostat is guaranteed in two stages. In case of a power outage or major incident, mechanically closing valves and buffer volumes ensure that the cryostat can return to a safe warm state without external intervention. Generally, the expanded process fluid remains enclosed in the cryostat, so that pressure relief valves and a ventilation system are only redundantly implemented for additional safety. To prevent hacker attacks and/or conscious or unconscious operating errors, there is an isolated small dual-core Cortex®-M7 + M4 microcontroller unit directly at the cryostat, which shares the sensors and actuators with the virtual system. The commands and data sent by the microcontroller to the cryostat actuators take precedence over those of the virtual controller, so that in case of an error, the microcontroller system takes over control and brings the cryostat back to a safe state. A special IO-Link master handles separating the bus systems of the virtual and microcontroller systems as well as prioritizing access to the sensors and actuators connected via IO-Link. Thanks to the high degree of virtualization, the control, sensor and measurement system of the research cryostats can be designed modularly, and individual components can be added dynamically - even during ongoing operation. The same applies to software applications, as the entire data stream, consisting of measurement, system and control data is standardized and stored in a database optimized for time series. Standardized interfaces enable the integration of long-term data analyzes and, in the future, the real-time integration of AI applications. The three main components of the virtual environment are the data flow programming application NodeRed, the InfluxDB time series database and Grafana for data visualization. All three software applications have an open-source license, which eases their use by different groups of people and collaboration between scientists from different affiliations. Thanks to the modular design, virtualization and the associated reduction in necessary hardware, our research cryostats can be built very compactly. This enables us to transport the cryostats and integrate them into existing experiments across Europe. For example, in August and November 2023, one of our research cryostats was integrated into an experiment at the Budapest research reactor to provide liquid parahydrogen to moderate neutrons, while in June, July and December 2023 it was in use at the prototype of the high-brilliance neutron source in Jülich.

Keywords: research cryostat, measurement system, control architecture, IO-Link, interface to AI applications, container virtualization, database, data visualization

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