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Controls and Data Acquisition Systems Architecture for the DOE STEP 10 MWe Pilot Scale sCO2 Power Plant

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ABSTRACT

The DOE STEP 10 MWe Pilot Scale sCO2 Power Plant lies in a niche between research-scale and utility-scale operation and requires a unique control and data acquisition system design to fulfill its many purposes. As an order-of-magnitude larger facility than many lab-scale set-ups, a commercial utility controls system is used for control, condition monitoring, and protection. However, as a research facility, data collection and accuracy are critical for success and require the use of a separate data acquisition system to achieve the level of performance desired. This paper describes the controls and data acquisition architecture used at the STEP plant in detail and explains the reasoning for design decisions such as the separation of controls and data acquisition systems, instrument and data redundancy, and others.

INTRODUCTION

The STEP 10 MWe Pilot Scale sCO2 Power Plant is a U.S. Department of Energy funded project led by GTI Energy in partnership with Southwest Research Institute (SwRI) and GE Global

Research. As the name of the project suggests, its goal is to design, build, and operate a pilot scale (10 MWe net output) sCO2 power plant on SwRI's campus in San Antonio, Texas. The plant will operate using a closed Brayton cycle, first in a simple recuperated Brayton and then in a recompression Brayton configuration. The working fluid sCO2 will pass through one of two compressors, one or both recuperator heat exchangers, a natural-gas externally fired heater, a turbine, and water coolers as part of the cycle.

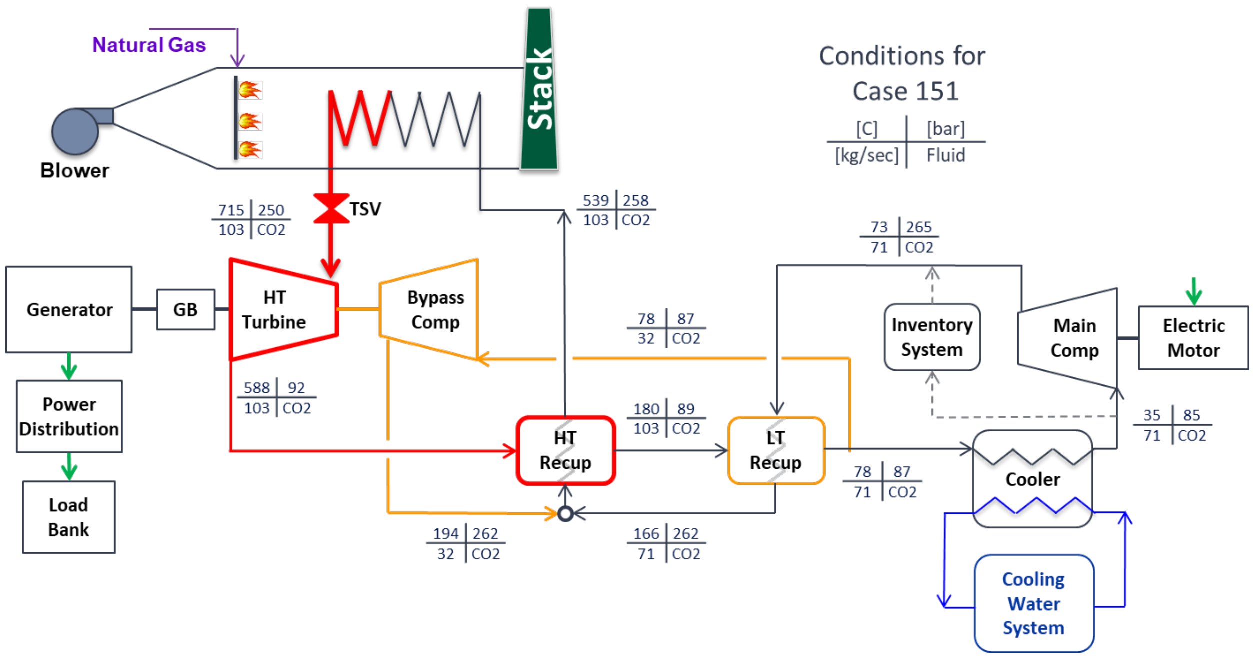

Figure 1 Recompression Closed Brayton Cycle Diagram

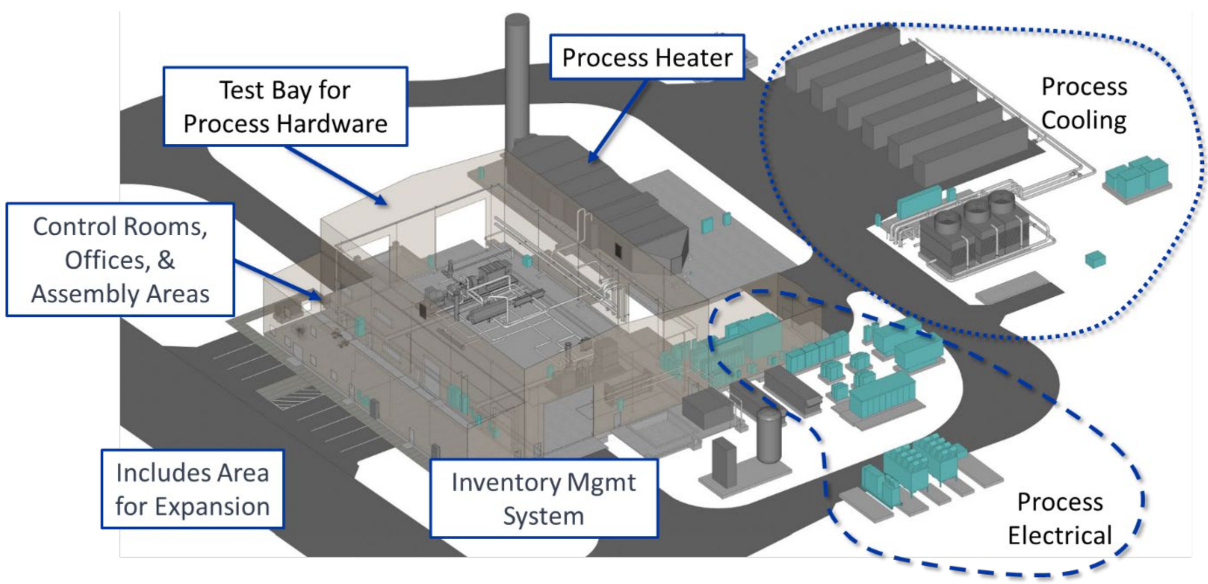

Figure 2 Preliminary 3D Rendering of STEP Facility

When completed, the plant will have over 600 pressure and temperature instruments installed and monitored, and more than 1200 I/O points when control and feedback signals are included.

Process control loops are required to maintain pressure and temperature set points at various points within the system. Vibration monitoring of spinning components is needed in order to quickly trip the process if vibrations are too high and risk damaging equipment. As a research plant, process pressure, temperature, and flow measurements are installed in a relatively larger quantity than is typical for a commercial application.

At this scale, an order of magnitude above typical lab-scale demonstrations, the number of interconnected sub-systems, control parameters, and instrumentation included in the plant design required a unique architecture for the controls and data acquisition system. The desire for the robustness and scalability of a commercial control system led to the purchase of a GE Mark Vie Distributed Control System (DCS) that serves to control and protect the plant during operation. The desire for measurement accuracy and flexibility in the computation and display of performance parameters led to the purchase of a separate NI LabVIEW-based Data Acquisition (DAQ) system that serves to provide high-accuracy, real time performance metrics as well as robust and reliable data storage for post-processing.

This paper will describe the architecture of the STEP controls and data acquisition systems in detail and seek to explain the reasoning for the many design decisions involved. The first section will discuss the DCS, and the second will discuss the DAQ system.

DISTRIBUTED CONTROL SYSTEM (DCS)

The STEP project, being a pilot scale power plant, wanted to select a DCS that was commercially scalable with high reliability and fast operating times (less than fifty milliseconds). The Mark VIe system was selected for these reasons, among others. It is capable of providing a ten-millisecond operation rate, which allows the control system to react quickly to any changes or issues with the system. GE was able to provide expertise from their Control Engineering staff, which has decades of experience programming DCS software for large-scale power plants. The Mark VIe system also provided an embedded PI historian that will be discussed in more detail later.

Once the GE Mark VIe system was selected for use, the hardware engineering phase began. A total of four workstations were needed: two for the control operators of the plant, one for the engineering workstation (the primary location for software and communication between the HMI's and the controllers), and one historian station, where long-term data would be collected and stored. The DCS requirements for Input-Output (IO) channels are shown in Table 1. The Mark VIe system architecture allows for distributed IO cabinets, so the team decided on two separate sets of IO cabinets. One is in close proximity to the turbine skid, and the other is in close proximity to the main compressor skid. After considering shipping provisions, the larger group of panels near the main compressor skid was split into two separate groups of panels.

Table 1 DCS IO Channel Requirements

IO Type	Quantity	Description of Signals
Analog	283	Pressure (static and differential), Valve demand and feedback, and setpoints to external PLC's
Discrete	231	Switches such as on-off commands and alarms

IO Type	Quantity	Description of Signals
TC/RTD	192	Temperature measurements

There are many IO points in the STEP facility because it is the first plant of its size with sCO_2 in a closed Brayton cycle. There are several methods of controlling the plant that still need to be understood, and the additional IO points will help the STEP team understand the physical processes occurring in the cycle. There are multiple sensors installed at critical locations for redundancy as well as a secondary way of calculating the performance information in case the DAQ system experiences an issue during operation.

The reliability of the Mark VIe DCS is enhanced by the redundancy built into the architecture. The primary function of the DCS is to control the STEP pilot plant and its associated subordinate PLC's for independent equipment. If the DCS fails to control the plant, it can be extremely dangerous and lead to equipment damage or injury to personnel. The DCS for the STEP facility is dual redundant. It starts with the controllers and flows through the networking infrastructure and down to the IO cards. The controllers communicate through the redundant network with the HMI's located in the control room. The basic architecture of the HMI's and controllers is shown in Figure 3.

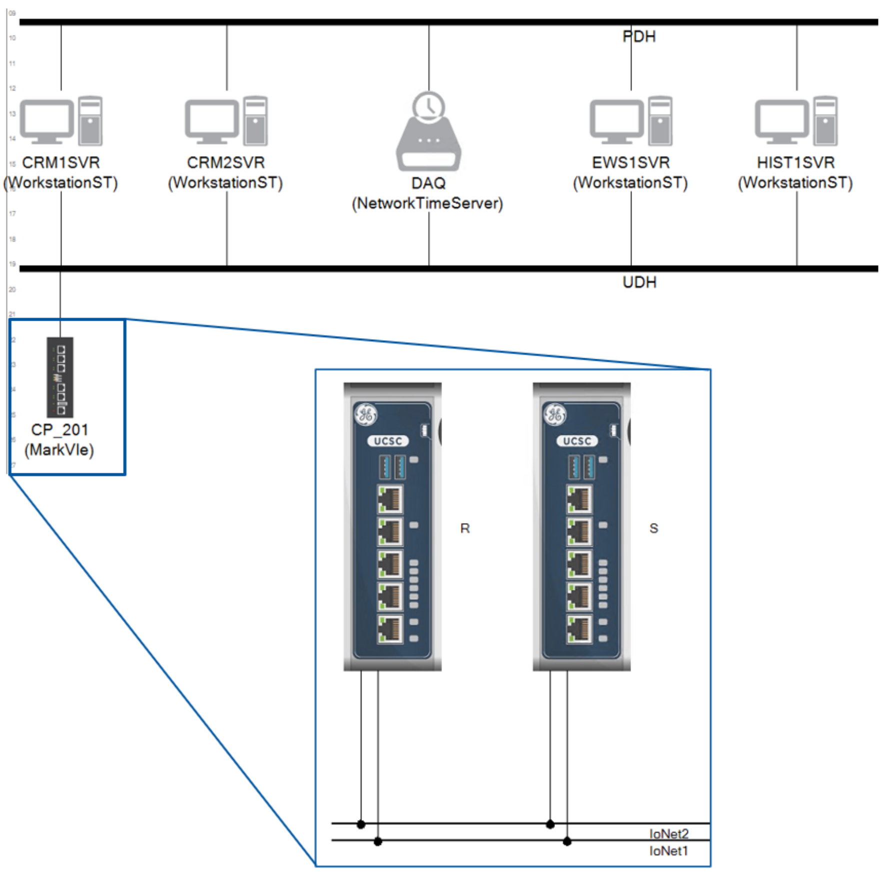

Figure 3 Dual Redundant Architecture Example

The DCS communicates with all of the independent systems using hard-wired connections for critical IO points, but also utilizes a Modbus network connection to gather an immense amount of data with very little wiring. The DCS acts as the master in this Modbus network and communicates with the other PLC's primarily using Modbus TCP, but also uses the Modbus RTU protocol. The primary Modbus layout is displayed in Figure 4.

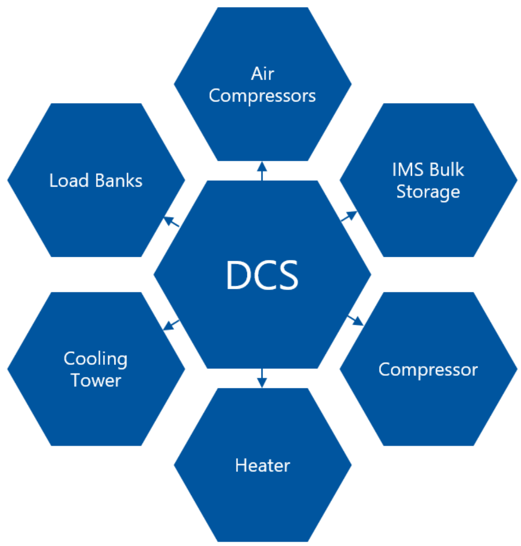

Figure 4 Main Modbus network connections to other PLC's

The DCS HMIs run on Cimiplicity software that is integrated with the ToolboxST suite (the software for the Mark VIe system). There are over 100 different screens set up to display all the information the DCS utilizes to run the plant, including the information delivered by the other PLC's through the Modbus network. The plant overview screen can be seen in Figure 5.

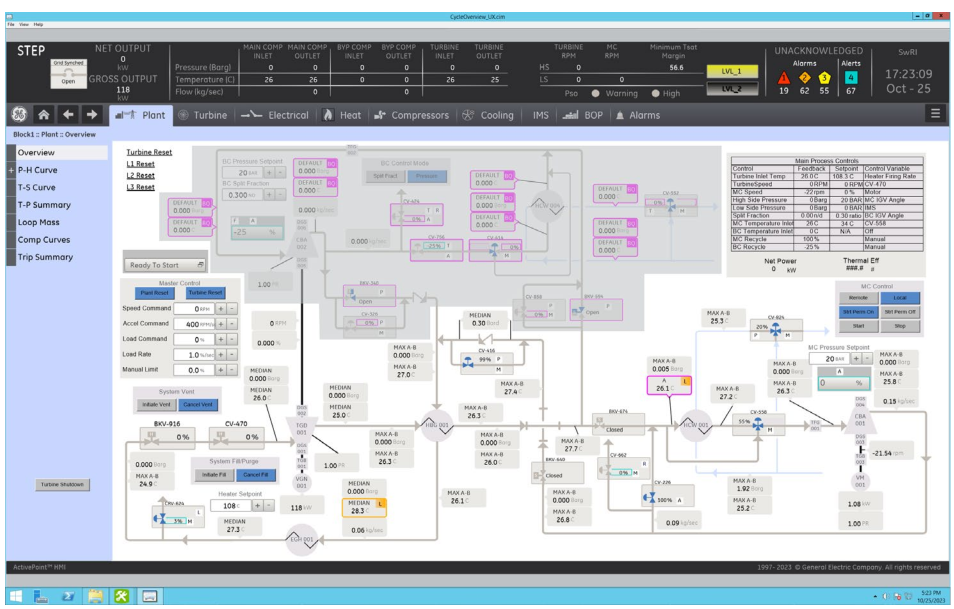

Figure 5 Overview screen for the simple recuperated cycle. The recompression section has a gray overlay

The last major component of the DCS is the historian. The Mark VIe ToolboxST software offers an integrated PI historian developed by Osisoft. The historian collects data from all of the process variables based on the deadband set for each signal. The version in use at the STEP facility allows up to 30,000 IO points. At the time of writing this paper, approximately 10,000 were set to be recorded.

DATA ACQUISITION (DAQ) SYSTEM

Unlike a typical commercial plant, or even a typical lab-scale system, the DAQ system for the STEP demonstration plant is separate from the controls system. While the GE Mark VIe DCS is a robust and reliable product, it is not designed for maximum measurement accuracy since research-grade measurements are generally not required for the safe operation of a commercial power plant. NI LabVIEW-based DAQ hardware is commonly used in R&D environments because of the flexibility of the hardware and software components that allows for rapid deployment and changes. Also, many of the available DAQ modules offer high measurement accuracies. Table 2 below compares the stated measurement accuracies of the measurement hardware selected for the STEP DCS and DAQ systems for analog and temperature measurements.

Table 2 DCS and DAQ Accuracy Comparison

System	**Analog (4-20 mA)**	**Temperature (°C)**
DCS	0.1% (Full scale)	1.1 - 3.3
DAQ	0.76% (Gain) / 0.04% (Offset)	0.7-1.1

The actual temperature accuracy for the DAQ system is expected to be better than the manufacturers' stated accuracy values, as end-to-end temperature calibrations are utilized for DAQ system thermocouples, and adjustments are applied to each channel based on this calibration data. An end-to-end calibration compares the raw temperature measured by the DAQ system using the actual cable as installed in the field. This helps to remove the error from voltage losses associated with cable length. Temperature accuracy is critical for the performance characterization of sCO2 power systems, as small changes in temperature near the critical point (typically at the compressor inlet) have an outsized impact on the machine and, therefore, the overall cycle performance.

The DCS analog measurement accuracy is better than the DAQ system's analog accuracy; however, the DAQ system's accuracy is sufficient for the purposes of this research program. Higher accuracy analog measurement cards are available from NI, but they have fewer measurement channels per card than the ones selected for STEP, leaving a trade-off between accuracy and channel count. The NI-9208 cards were selected due to their higher channel count and sufficient accuracy.

Another advantage in using a LabVIEW-based system is leveraging the extensive codebase that SwRI has developed for use in other machinery labs. Use of this existing codebase reduces development time significantly and allows the use of existing LabVIEW expertise when making changes or modifications.

The DAQ system monitors 261 pressure and temperature instruments in the facility. This includes 85 static and 50 differential pressure transducers as well as 126 thermocouples. Several of these instruments are used in conjunction with orifice plates to measure flow at 18 different locations. As a research plant, one of the primary goals is to collect performance data and understand the cycle and system performance. If performance data is not being collected during operation, there is little value in continuing to operate. Starting up and shutting down the plant can be costly in terms of both time and money, so it is necessary to ensure there is always at least one functioning sensor at all key locations, even if a sensor was to fail. While the DCS uses sensor redundancy to ensure the ability to control the process even with the loss of a sensor, the DAQ uses sensor redundancy to ensure useful performance data is always being collected.

Figure 6 Pressure and Temperature Instruments Used

The DAQ system utilizes a distributed arrangement of data collection nodes. Multiple measurement chasses are strategically spaced throughout the facility to reduce the total length of sensor cables to be run. Each of the five distributed chasses reside in a junction box, to which cables from nearby sensors are run and connected to their designated channel for measurement. The chasses selected were NI's cRIO-9047, with NI 9214 thermocouple modules and NI 9208 analog signal modules. The cRIO series of chasses are essentially small computers, capable of standalone operation and local data storage.

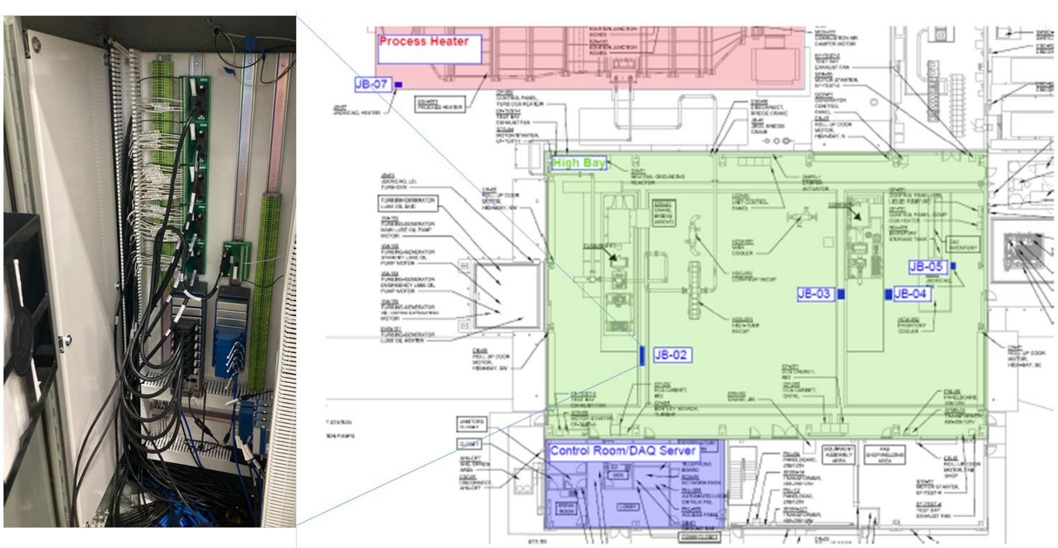

Figure 7 Locations of distributed chasses throughout facility

Figure 8 NI cRIO chassis and associated analog and temperature measurement modules

Each remote chassis is connected to an isolated DAQ network, which includes the Primary PC. This PC is responsible for collecting and processing the data from each remote node in one location. Processing this many data points and the associated performance calculations requires a very capable computer, so the selected primary PC contains a large amount of RAM, a powerful CPU, and multiple large hard drives for data storage.

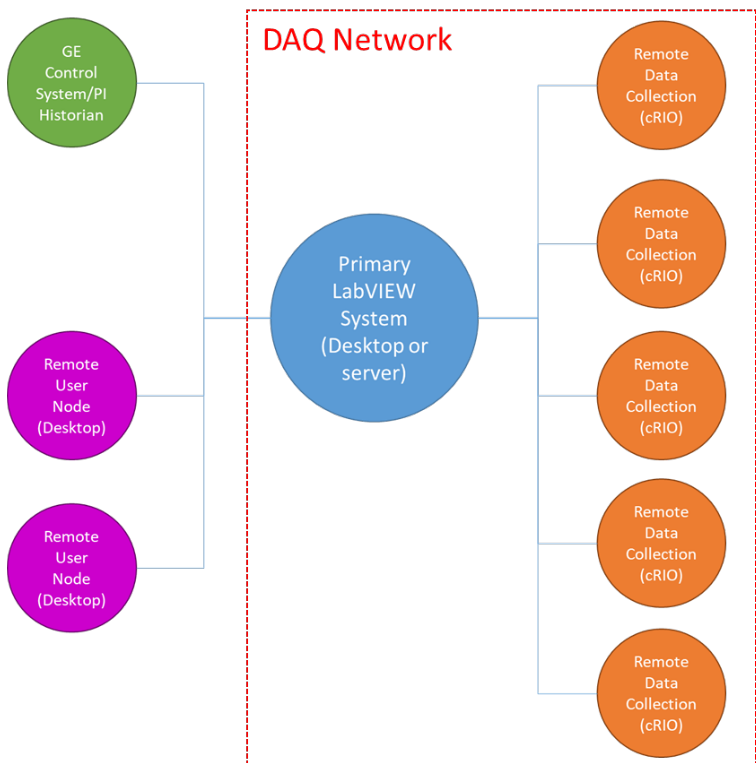

Figure 9 DAQ Network Schematic

During operation, each cRIO chassis takes measurements on its defined channels and immediately performs some minimal processing (scaling of data to engineering units) before passing the data along to the Primary PC. When powered on, each cRIO boots immediately into data collection mode, and is always collecting data locally whenever it is on. By default, it deletes local data older than a specified period of time. While connected to the primary, the system works to ensure that all local data generated while connected is transferred to the primary. There is also a software option to delete data only after it has been successfully transferred to the Primary PC. This option is typically enabled during operation so that even if connection is lost to the Primary PC, no data is lost as it remains on the cRIO's local storage. Upon reestablishment of the connection, data transfer resumes, and the backlog of locally stored data can be cleared.

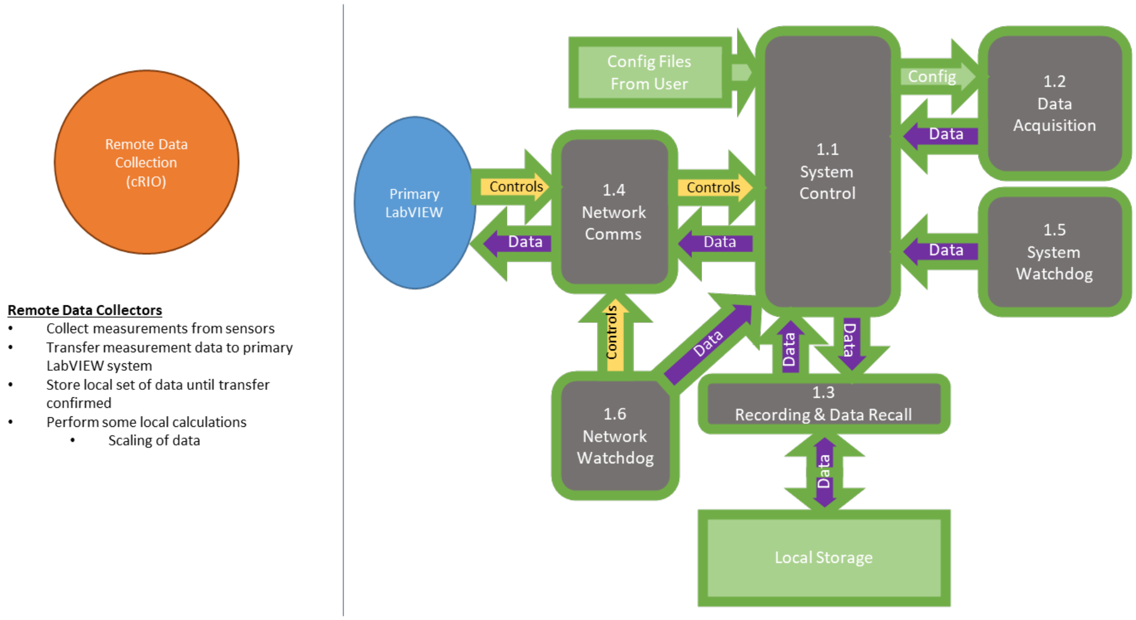

Figure 10 Remote cRIO software flow schematic

The Primary PC, when connected to the cRIOs, takes the raw data from the cRIOs and processes it in several ways. One preliminary processing step is to perform time averaging and timestamp alignment so that the processed data is recorded at the beginning of the second with a 1-second frequency. Raw data is collected at 25 Hz for analog measurements, and 4 Hz for temperature measurements. Processed data is always stored on the Primary PC during operation.

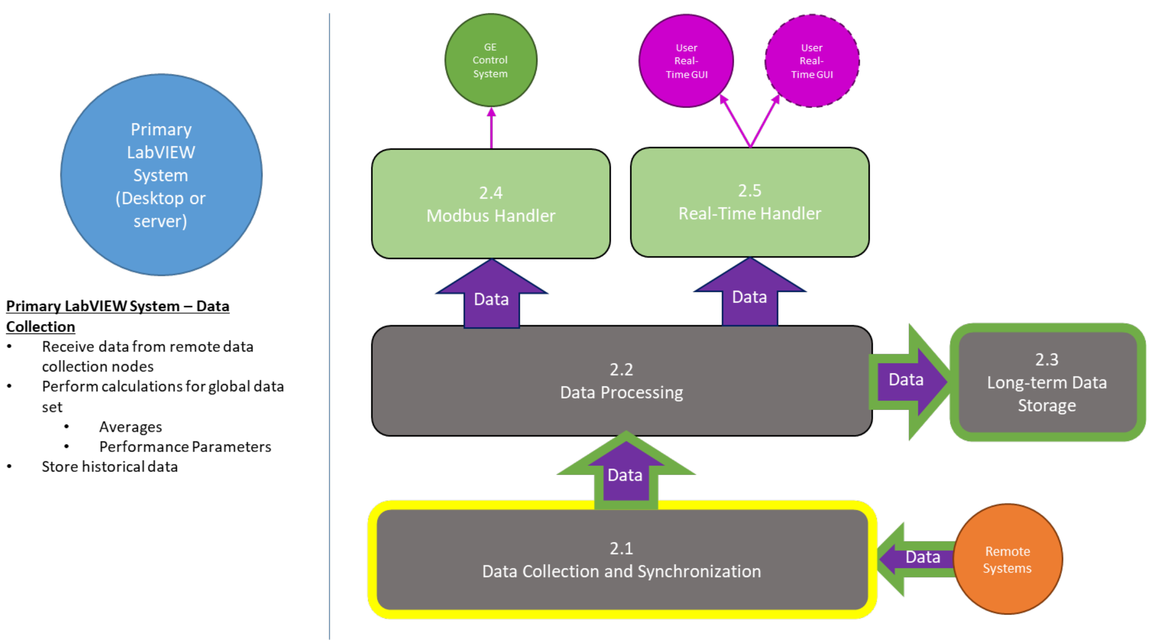

Figure 11 Primary PC software flow schematic

The Primary also performs sensor averaging between redundant sensors at a location. Part of this process includes checking the health or “quality” of a sensor and excluding it from the average if it is deemed unhealthy. One of these checks involves a comparison of the measured value to a set of minimum and maximum thresholds outside of which the sensor may be believed to be unhealthy. Another check performed by the Primary is to calculate the average and standard deviation of a group of redundant sensors, and to exclude any sensor that lies more than two standard deviations away from the average. Sensor quality is carried through into any calculation where the sensor is used. For example, if all sensors measuring compressor suction pressure are in fault, then all calculations requiring compressor suction pressure (such as compressor efficiency) will also show a quality in fault. This quality is carried through into any subsequent calculations using values that can be traced back to the faulted value.

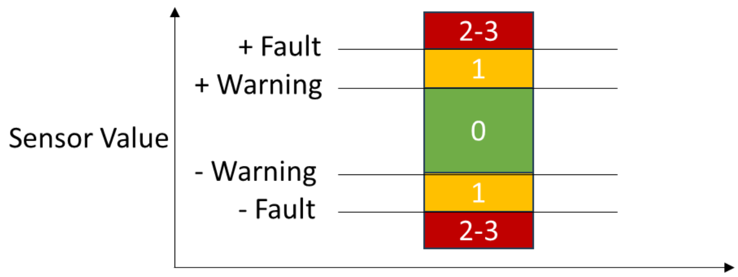

Figure 12 Sensor quality range general example

The Primary PC software utilizes a watchdog program to periodically check the health of the various network interface programs on the Primary PC. If one of these interface programs is found to be frozen or non-functional, the watchdog can close and restart the program to reestablish the connection. As shown in Figure 13, the primary PC runs two other interfaces: one to a remote Graphical User Interface (GUI) PC, and another to a Modbus client on the DCS.

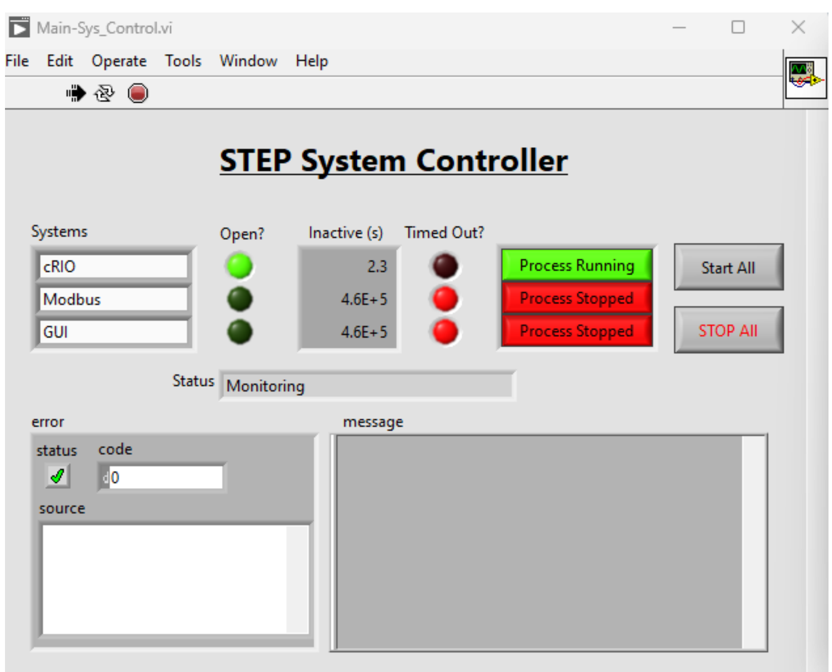

Figure 13 Primary PC software controller and watchdog

The GUI interface passes processed data to a separate GUI PC for real-time viewing of plant DAQ data and performance calculations. This GUI PC is used purely for data viewing and has no control functions, just like the rest of the DAQ system. The separately developed software package for the GUI provides pre-developed screens for viewing sensor and calculation qualities, component performance and health monitoring, current cycle state points, and strip charts showing sensor and calculation values over the previous 10 minutes.

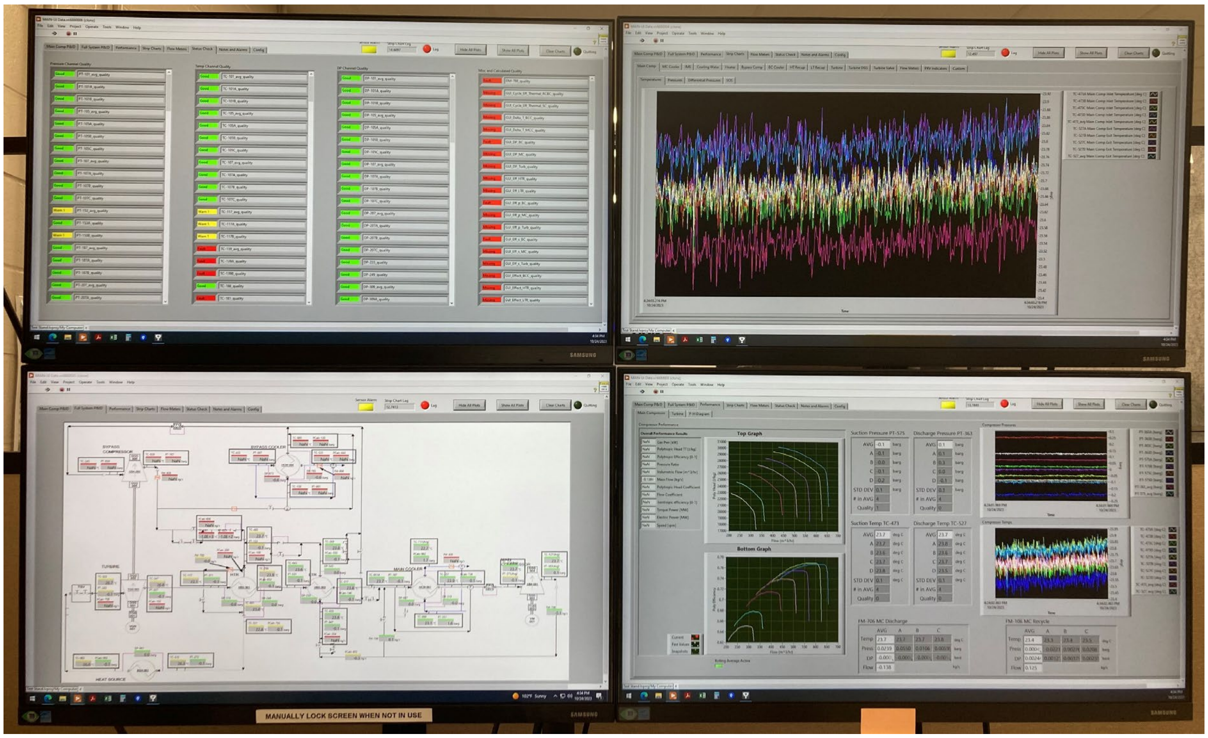

Figure 14 Multiple monitor set up on the GUI PC for live data viewing

The Primary PC hosts a Modbus server that is polled by the DCS Modbus client to gather key DAQ performance data and store it alongside control data in the facility PI Historian. Hosting DAQ and DCS data together can help with troubleshooting and analysis, as it is possible to verify valve and alarm statuses at a given point in time. The Primary PC also hosts a time reference server that the DCS uses to synchronize its data timestamps with those of the DAQ.

SUMMARY

From a controls and data acquisition perspective, the STEP facility has a unique blend of industrial-sized scaling and operations requirements as well as high-value research data requirements. This led to the decision to install separate controls (DCS) and data acquisition (DAQ) systems to achieve the best of commercial system reliability and scalability, as well as research system measurement accuracy and data quality. The GE Mark VIe DCS allows the STEP facility to show how an existing commercial product may be utilized to control a sCO2 power cycle at scale. The NI LabVIEW-based DAQ system allows the STEP facility to maximize data accuracy and reliability so that system operation time is used most impactfully. Together, the two systems work in tandem to ensure the safe, reliable operation of the pilot plant and the successful execution of the STEP research program.

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