2009 American Control Conference
Hyatt Regency Riverfront, St. Louis, MO, USA
June 10-12, 2009

ThB02.1

Bridging the Gap between Universities and Industry

Terrence L. Blevins and Gregory K. McMillan

Abstract—**The distributed control system (DCS) is the most prevalent means of implementing batch and continuous control in the process industry. The DCS platform may also be effectively used for the evaluation and demonstration of innovative algorithms developed at a university. The integrated online advanced controls, diagnostics, data analytics, and process modeling capability of a DCS facilitate university research. This working environment also prepares students for careers in industry. The paper discusses the industrial standards adopted by the DCS that allow students and researchers to concentrate on the application of new control capabilities. External applications such as Matlab can be used with the DCS to explore control and process modeling. In this environment, the student and researchers may take advantage of preconfigured and automated features of the DCS. Process simulations may be integrated into the DCS to create a virtual plant capability that is capable of running faster than real-time. The DCS supports wireless and internet access to the virtual plant which increases ease of use in a lab or pilot plant. The DCS system enables rapid exploration, discovery, and prototyping of process modeling and control technologies in a university environment and deployment in industry.**

I. INTRODUCTION

THE architecture of distributed control systems, DCS, has evolved significantly since the initial introduction of DCS systems in the late 1970's. Much of this change has been driven by the ever increasing performance-price ratio of the associated hardware. The evolution of communication technology and of supporting components has dramatically altered the fundamental structure of the control system. Communication technology such as Ethernet and TCP/UDP/IP combined with standards such as OPC allow third party applications to be easily integrated into the control system. Also, the general acceptance of object oriented design, software component design, and supporting tools for implementation have facilitated the development of better user interfaces and the implementation of re-usable software. A new generation of process control systems based on these developments has been introduced by major control system suppliers. These systems incorporate commercially available hardware, software and communications. They integrate Bus Technology such as Fieldbus and Profibus fully into the system. Batch Technology and Advanced Control are included as embedded technologies within the system.

These new systems provide a solid foundation that meets the instrumentation and control system requirements of university research labs and pilot plants.

II. SOFTWARE ARCHITECTURE

The functional components that make up a modern DCS may be illustrated as shown in Fig. 1. Distributed Control Systems are made of several components including workstations, controllers, IO Cards, IO Buses, a control network, control technology and software. The controllers are connected to field devices via analog, digital or combined analog/digital buses. The field devices, for example, valves, valve positioners, switches and transmitters (e.g., temperature, pressure, level and flow rate sensors), are located within the process environment and perform process functions such as opening or closing valves, measuring process parameters, etc. The controllers hold control strategies which often encompass control strategies distributed across field devices. Control strategies in controllers send signals over the communication lines to the field devices to control the operation of the process.

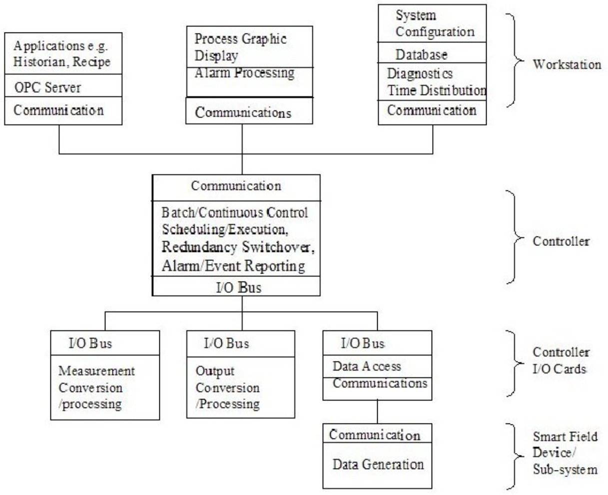


Fig. 1. Functional components of a Modern Digital Control System.

Information from the field devices and the controller is made available over a control network to operator workstations, data historians, report generators, centralized databases, etc. These nodes run applications that may, for example, enable a student to perform functions with respect to a physical or simulated process, such as changing settings

---

Manuscript received March 12, 2009.

T. L. Blevins is with Emerson Process Management, Austin, TX 78759 USA(512-418-4628;fax:512-418-7500;e-mail: terry.blevins@Emerson.com).

G.K. McMillan was with Monsanto and Washington University in Saint Louis. He is now with Emerson Process Management, Austin, TX 78759 USA. (greg.mcmillan@Emerson.com).

978-1-4244-4524-0/09/$25.00 ©2009 AACC

of the process control routine, modifying the operation of the control modules within the controller or the field devices, viewing the current state of the process, viewing alarms generated by field devices and controllers, simulating the operation of the process for the purpose of testing the process control software, keeping and updating a configuration database, etc.

A configuration database, which resides in a DCS, enables users to create or modify control strategies and download these strategies via the Control Network to dedicated distributed controllers. Typically, these Control Strategies are made up of interconnected function blocks, sequential function charts (SFC's), Equipment and Units representations, etc which perform functions within the control scheme based on inputs and which provide outputs to other function blocks and/or IO within the control scheme. The configuration application also allows a student to create or change operation displays to view process data or to change settings, within the process control system. Each controller stores and executes a controller application that runs the control modules assigned and downloaded to implement actual process control functionality.

A critical aspect of the DCS is its integrated alarms and events system. The system provides configuration, monitoring, and notification of significant system states, acknowledgements, and priority calculations. Events represent significant changes in state for which some action is potentially required. In most systems event types can also be defined. The event type specifies the message to be displayed for the various alarm states, and the associated attributes value that will be captured when an event of this type occurs.

Integrated diagnostics is a standard feature of the DCS. The diagnostics cover the hardware, redundancy, communications, control, and to some extent, the software that makes up the DCS.

III. PHYSICAL STRUCTURE

The major components that make up a process control system [7] are illustrated in Fig. 2.

The operations interface is typically made up of standard off-the-shelf personal computers, PC's, standard keyboards, mice, and CRT or LCD monitors. Similarly, personal computers are utilized for the maintenance and engineering stations and application stations that are utilized for system configuration and diagnostics and for the integration of third party software into the control system. Standard operating systems such as Windows XP and Vista are commonly provided in these stations.

The communication link from the controller and the PC's that make up operation, engineering and application stations is a key feature of the process control system. In most cases the deterministic communication of process alarms and values is achieved using Ethernet interfaces operating at communication rates of 10Mbit or 100Mbit. The PC communication interface may be designed to utilize two Ethernet interface cards, making it is possible to provide fully redundant communications.

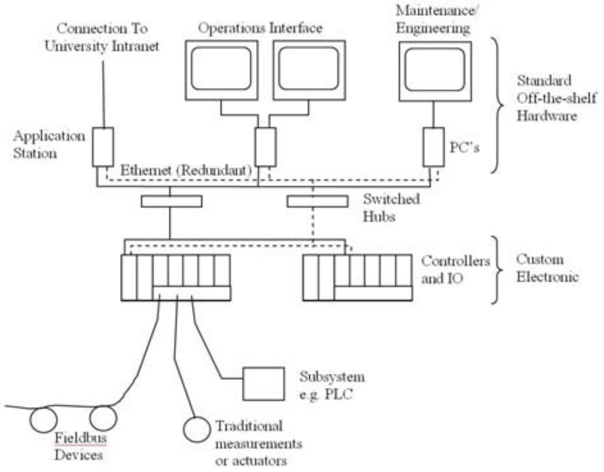


Fig. 2. Physical Structure of Digital Control System.

The requirements for redundancy and interfacing for I/O processing dictate that the process controller be a custom hardware design. Also, a real-time operating system for embedded applications is often used to provide deterministic scheduling and execution of control.

A large variety of I/O cards are normally provided to address a variety of field measurements and final elements:

- Analog Input (isolated) 1-5 volt DC, 4-20ma
- Analog Output 4-20 mA
- Isolated RTD and Thermocouple Input
- Discrete Input 24 VDC, 120/230 VAC
- Discrete Output 24 VDC, 120/230VAC
- Pulse Count Input
- Pulse Duration Output

Since digital transmitters and final elements that utilize a variety of communication protocols and physical interfaces are available, many manufacturers offer interfaces to the most common buses. Also, serial interfaces cards are often supported for interfacing to subsystems such a programmable logic controllers, PLC's. Examples of these communication interface cards are:

- HART AI-Card and AO-Card
- DeviceNet (Baud rate 125 250 500 Kbit/sec)
- FOUNDATION Fieldbus
- AS-Interface
- Profibus DP Baud rate (9.6 19.2 93.75 187.5 500 1500 Kbit/sec)
- Serial Interface (Modbus or Allen Bradley's

Data Highway Plus protocol).

In addition, some manufacturers may offer I/O cards to meet special requirements. For example, Sequence of Events (SOE) input cards are used to capture process-upset events coming directly from devices in the field. For example, events captured by an SOE input card may be time stamped using a ¼-millisecond resolution.

A. *Integration with Busses*

The adaptation of the IEC1158-2 fieldbus standard by the major DCS manufacturers has ushered in the next generation of control and automation products and systems. Based on this standard, fieldbus capability may be integrated into a DCS system to provide:

- Reduced wiring and installation costs.
- Provide increased information flow to enable automation of engineering, maintenance, and support functions.

The bus design largely determines the types of devices and applications that may be effectively addressed to implement an application.[6] For example, the Profibus[3][4], AS-Interface and DeviceNet bus technologies are optimized for fast access of discrete information and best address applications such as motor control and discrete part manufacturing. Conversely, buses such as Foundation Fieldbus and Profibus PA address the specific requirements associated with continuous control applications.

Most modern DCS systems provide controller cards that are designed to support the physical and communication interface associated with each fieldbus technology. Furthermore, the same configuration, diagnostic, and operator interface techniques can be used to configure the system, enabling users to match bus technologies to application requirements.

Fieldbus networks are designed to provide bi-directional communications between "Smart" sensors and final elements and a control system. An Electronic Device Description (EDD) language has been defined by the IEC 61804 standard that allows the DCS to use devices based on different technologies and platforms. The IEC 61804 standard contains profile conformance statement for numerous technologies including PROFIBUS™ and Foundation Fieldbus®. Thus, a modern DCS system that integrates fieldbus devices may be illustrated as shown in Fig. 3.

B. *Integration with Wireless*

Another new technology is wireless. For some applications, such as rotating machinery, getting measurements may be difficult. In other applications, such as equipment and process monitoring, wireless provides a whole new way to interact with the process. In these cases wireless instrumentation such as WirelessHART enables unit-level process operations and supports applications such as:

- Equipment and process monitoring;
- Flexible process research and development
- Asset management;
- Diagnostics/ predictive maintenance;
- Process control
- Nomadic, "wireless worker" applications

C. *Interfacing to Subsystems*

Many new and existing DCS systems include a hardware interfaces that utilize a common communication protocol such as MODBUS to transfer information from another device such as a programmable logic controller, PLC. MODBUS is a popular method for moving data values between systems. It is an application layer messaging protocol, which provides client/server communication between devices connected on different types of buses or networks. MODBUS support is provided across both serial as well as TCP/IP networks.

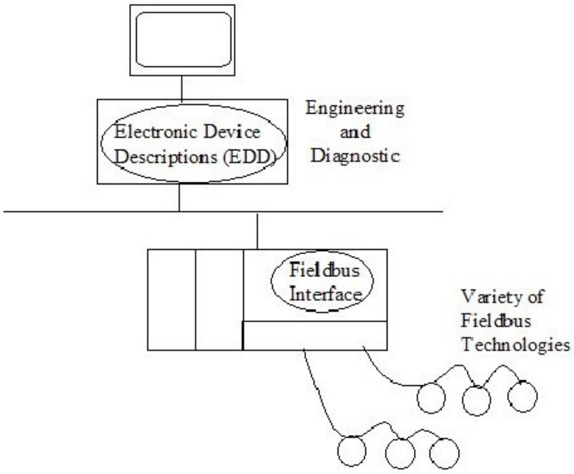


Fig. 3. Fieldbus Interface in the DCS

D. *Interfacing to Other Applications*

Modern process control systems support information exchange based on the OPC Foundation's Data Access Specification [2]. This process industry standard was created through a collaborative effort of leading automation suppliers and Microsoft. The specification defines a standard set of objects, interfaces and methods that facilitate interoperability. OPC may be used to exchange a large number of parameters between a control system and an external application such as Matlab. Applications such as Matlab offer standard support for OPC. Using OPC, an application can access real-time data, alarms and events, and historian data as illustrated in Fig. 4.

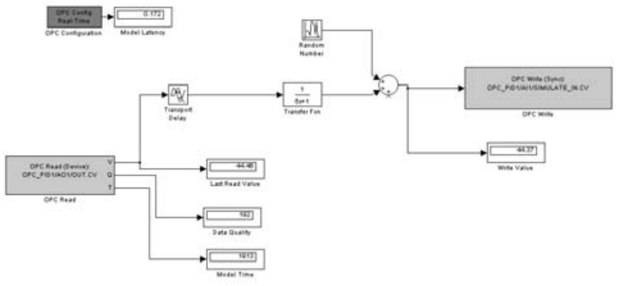


Fig. 4. Using Matlab OPC Interface to DCS

E. Data Collection for Analysis

The DCS usually includes the ability to collect batch, continuous, and event data. A centrally defined history database is available for the storage of historical data. The value of any attribute, alarm of any control strategy, alert, or process condition can be recorded in the history database along with its status. In modern control systems the data values are collected as an integrated feature of the system. Events are collected and time stamped at their source – in some cases down to a few millisecond resolutions. Users and layered applications such as Matlab can utilize OPC to retrieve the batch, continuous, and event data in a time-ordered fashion.

F. Operations View

The viewing applications, which may run on one or more operator workstations, receive data from the controller application via the control network and display this data to the system user. A number of different views, such as an operations view, an engineer view, and maintenance view, provide function focused information and interface.

Operation display applications are typically implemented on a system wide basis in one or more of the workstations and provide preconfigured displays that may be used by a student or maintenance persons to view the operating state of the control system or the devices used for measurement and actuation. These displays are generally preconfigured to display, in known manners, information or data received from the control modules or the devices within the process plant. Displays may be created using pre-defined objects that have a graphic associated with a physical or logical element and that is tied to the physical or logical element to receive data about the physical or logical element [9]. The object may animate the graphic on the display screen based on the received data to illustrate, for example, that a tank is half full, to illustrate the flow measured by a flow sensor, etc. An example of an operator display created using a library of 3D components is illustrated in Fig. 5.

A variety of data sources may be integrated into the process display graphics. The data may be sourced internal to the DCS from the runtime, historians (continuous, batch, event), and alarm services. The data may also be sourced externally from OPC, XML Files, or even an HTTP Browser. Supporting both internal and external data sources allows the operation displays to be used for a wider range of functions.

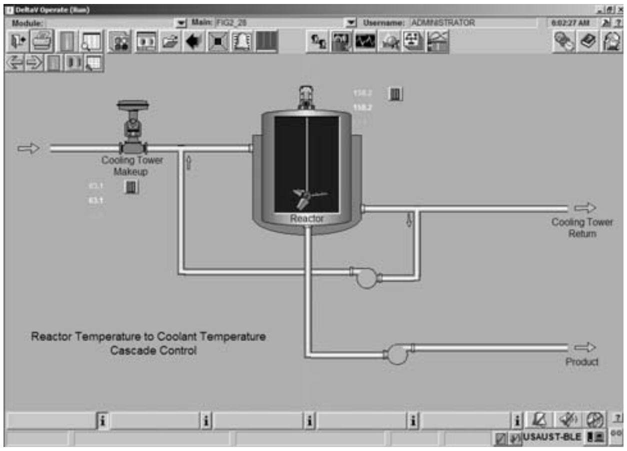


Fig. 5. Example operator graphic display.

G. Consolidated Database

One of the most critical features of the control system is the collection and maintenance of the control system configuration within a database. The capability may be provided to allow any change in the system to be automatically recorded i.e. when the change was made and who made the change. Also, a provision may be provided to undo any changes in the system.

In a distributed control system there must be a consistent means of representing and referencing information. Ideally, such reference can be made independent of the physical device that holds this information. A common way to accomplish independence is to conceptually divide data within the control system into units that are assigned a unique identifier known as a tag. The S88 batch standard defines such logical grouping of measurement, calculation or control as a module. When a control system follows this convention, then each module is assigned a tag that is unique within the control system. Based on this tag and the structure of the components in the module, it is possible for applications in the control system to reference any piece of information.

IV. CONTINUOUS AND DISCRETE CONTROL

With the introduction of the IEC 61131-3 standard in the early 90's, most manufacturers began to provide general support for graphic control implementation. The IEC 61131-3 standard defines four control languages for use within the process control and manufacturing automation areas [8]. Three of these languages were based on a graphical representation of the control.

Function Block – Allows both continuous and discrete control to be represented as re-usable blocks of functionality. The information flow between blocks is defined by graphically wiring between the function block input and output connections. For example, the graphical function block representation of a cascade control loop is shown in Fig. 6.

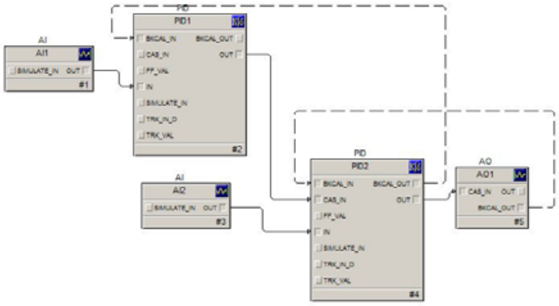


Fig. 6. Function Block Example of Cascade Control

Sequential Function Chart – Supports the definition of calculation and control where the logic evaluation is done in a sequential manner and may follow different paths depending on operating conditions. Such capability is often required in sequential control as utilized in the batch industry. An example SFC is shown in Fig 7.

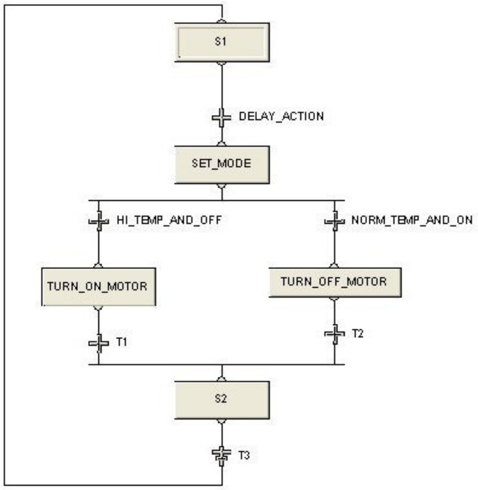


Fig. 7. SFC Step and Transition Representation

Ladder Diagram – Allows discrete logic to be implements as rungs of contact, coils and function blocks. Such implementations have been utilized primarily for implementation of discrete control and the associated interlock and permissive logic in such applications as motor control.

The use of function blocks for control in the process industry has been advanced by major equipment manufacturers and end users through the creation and support of Foundation Fieldbus and Profibus organization. Many of the fieldbus devices utilized in the process industry today are based on the Function Block specifications defined by the industry sponsored organizations. The IEC 61804 international standard for process industry function blocks has adopted much of the function block architecture of Foundation Fieldbus and Profibus [5].

V. ADVANCED CONTROL

Recent advances in the processing power available within a control system allow advanced control capability to be embedded in the control system [11]. This embedded advanced control includes:

- Loop Tuning
- Fuzzy Logic Control
- Model Predictive Control
- Property Estimation e.g. Neural Network

This new generation of advanced control is often designed so that the average process engineer may use these features with the same confidence as traditional control. Fuzzy logic control, model predictive control, and property estimation may be implemented as a function block that can be assigned to execute in the standard redundant controllers. For this embedded implementation, the engineering tools for the configuration and troubleshooting of traditional control may also be used with these advanced control blocks. The MPC control definition for a relatively simple multi-variable control strategy is shown in Fig 8.

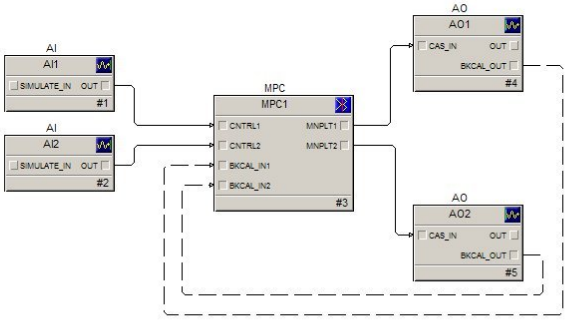


Fig. 8. MPC Application Example

On the small processes targeted by embedded MPC control, such features as automated testing of the process are provided as part of the MPC engineering tools [12]. Once data is collected, the process model and controller can be generated automatically. The automation of the implementation makes it possible to create labs in which students utilize advanced control with physical or simulated processes within the session time constraints.

VI. PROCESS AND CONTROL SIMULATION

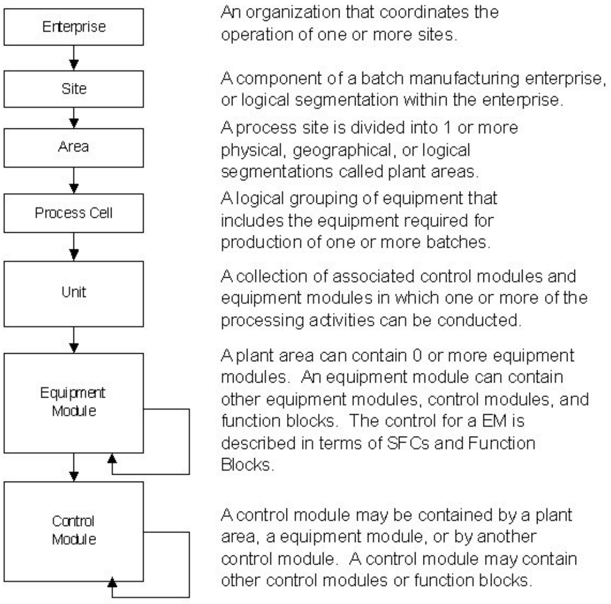
High fidelity dynamic process simulation packages or process simulations created using Matlab may be easily integrated into a modern DCS through an OPC interface [1]. The behavior and influence of the control system be included in such a dynamic simulation by allowing the IO inputs used in control modules to be read and written by the process simulation. All features of the control system may be executed on a single PC platform or distributed between multiple computers to create a “Virtual DCS”. This capability to combine process and control simulation allows labs to be created to give students experience creating and using continuous and discrete control techniques under a variety of conditions and supporting features such as diagnostic and alarming capabilities provided by a DCS[10]. Depending on the modeling rigors and computing resources, the process simulation used in such exercises can potentially run faster or slower than realtime. To allow the control to match the process simulation execution, support may be provided in the DCS to execute function blocks faster or slower than real-time.

VII. BATCH CONTROL

The ISA S88 Standard for Batch Control has been adopted by DCS manufacturers to provide a standard means of defining recipes, equipment handling, and formulation of batch control [13]. This standard defines a hierarchy of modular control that supports reusable control components. The standard also provides for flexibility by allowing a recipe to determine the product related characteristics of a process, while equipment control functions are imbedded in the reusable modules. Further, the standard defines and gives names to the modules that are in continuous and discrete control – referred to as ‘basic control’ in the S88 standard. The standard also defines a layer of procedural control that allows sequences of control actions to step a process through a recipe-defined procedure. Moreover, the standard defines coordination control which keeps all the other pieces and parts properly sorted. Overall, the S88 Standard has provides an efficient means for collecting data in an understandable way from a process that, by its nature, is constantly changing state.

S88 was adopted as an ANSII standard and has become an international standard (IEC61512-01). The basic structure of the S88 standard is illustrated in Fig 9.

Exposing student to the basic concepts of batch control is appropriate for students that focus on control since batch processes are common in key industry segments such as pharmaceutical and specialty chemical manufacturing.



An organization that coordinates the operation of one or more sites.

A component of a batch manufacturing enterprise, or logical segmentation within the enterprise.

A process site is divided into 1 or more physical, geographical, or logical segmentations called plant areas.

A logical grouping of equipment that includes the equipment required for production of one or more batches.

A collection of associated control modules and equipment modules in which one or more of the processing activities can be conducted.

A plant area can contain 0 or more equipment modules. An equipment module can contain other equipment modules, control modules, and function blocks. The control for a EM is described in terms of SFCs and Function Blocks.

A control module may be contained by a plant area, a equipment module, or by another control module. A control module may contain other control modules or function blocks.

Fig. 9. S88 Control Hierarchy

VIII. REMOTE ACCESS TO DCS

Modern DCS systems are designed to support plant wide access to real-time DCS information. To provide an open interface, this capability is typically based on international and industry standards. In most cases, these will consist of support for:

- Ethernet physical communication layer.
- Internet connection support for remote access to plant information
- WIFI wireless access to operation data
- Modern operating system, such as Microsoft .Net framework, to provide XML data exchange and support for Terminal Server Capability

These technologies may be combined in a modern control system to address information access requirements.

Using this capability, a student with access to the university intranet may use their laptop or workstation to access the DCS. Also, where the student has been given configuration privilege, it is possible for students to simultaneously configure control and displays. The network integration may be illustrated as shown in Fig. 10.

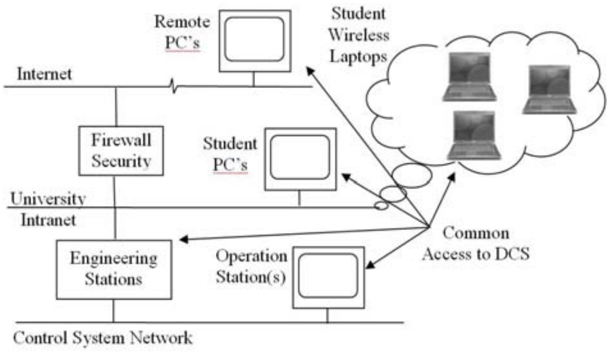


Fig. 10. Remote Access to the DCS

Through the use of OPC and XML technology, a common means of information access is provided within the control system at remote locations. The capabilities of modern operating systems such as Microsoft XP and Vista allow the same interface to be utilized to display realtime information. The advent of wireless communication standards, such as IEEE 802.11b, WIFI, and adoption of this technology by laptop manufactures allows realtime data and configuration information within the control system to be accessed throughout the university. In such an environment, strict implementation of security to authenticate user access to the control system is crucial to system maintenance. Also, any provision that the university makes for internet access to the control system usually includes some kind of firewall, a secured connection, and in some cases, data encryption.

Ethernet routers and switches may be incorporated into the communication system to limit information. Routers and switches are also used to ensure that when DCS information is accessed via the LAN or remote applications, then it has no impact on control system communication.

Plant network interfaces are being used in some universities to allow students to work on control labs and experiments. As DCS networks become more prevalent in universities a fundamental shift is occurring in how students are trained on process control.

IX. SYSTEM MAINTENANCE

Security is a major part of the DCS. The DCS manages what a user is able to do by User, Process Area, and Workstation. Layered applications have to form a session before they are allowed access into the system. There are several aspects to security as summarized below:

- Authentication – access to the DCS for human users and layered applications users will be controlled through the use of password protected user accounts.
- User – a human user of the DCS must have a user account on the system in order to gain access.
- Area Security – a user account can be permitted or denied access to make changes within zero or more areas within a site.

For each area where access is permitted, access can be restricted at runtime according to the classification of the runtime attribute data can be changed. For each plant area where access is permitted, the ability to make configuration changes can be restricted.

A user account can be permitted or denied access to view or modify user account and privilege information. In some systems it is also possible to enable authorization. In these cases a user, or in some cases several users, will need to confirm by password the changing of certain parameters, starting/stopping a batch, etc.

X VIRTUAL PLANT

Dynamic external or embedded process models can write to the simulation inputs and read the outputs of function blocks. The DCS can be an actual hardware system or virtual version of the DCS residing in a personal computer or a DCS application station. The use of industrial standards in the DCS and the associated terminology can provide a common basis for communication and evaluation of model based control technologies between universities and industry.

External models are typically interfaced to a “hardware DCS” via a Virtual I/O Module (VIM), which provides an Ethernet connection between external simulations via an I/O driver and interface table [14]. For the “virtual DCS”, OPC is used to interface external simulations. The same model can be used as one moves from the “virtual DCS” to a “hardware DCS” in the commercialization process. The speedup of external process models can present coordination problems. The real-time factor of the simulation should be adjustable and achievable even for extreme upsets. The control system realtime factor should be the same as the model realtime factor for identification of dynamics and controller tuning.

The “virtual DCS” is not an emulation or translation but is a virtual replication of a complete DCS with all of the standard and optional advanced tools. Control system trend charts, displays, configurations are exchanged between a “hardware DCS” and “virtual DCS” by standard copy, import, export, and download functions. The incorporation of process models in a “virtual DCS” creates a “virtual plant”, which offers an opportunity to integrate and build process knowledge with the “state of the art” advanced tools for Process Analytical Technology (PAT) and Advanced Process Control (APC) as depicted in Fig. 11 [15] [16].

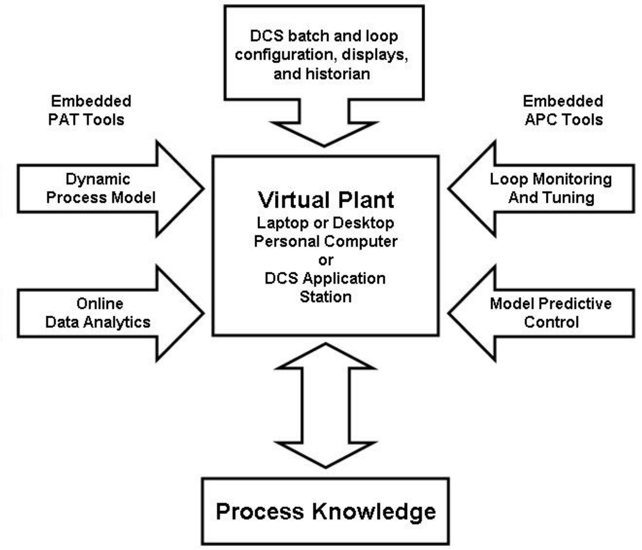


Fig. 11. The Virtual Plant offers the synergy of integrating and building process knowledge through the use of embedded Process Analytical Technology (PAT) and embedded Advanced Process Control (APC) tools.

Dynamic first principle process models have been embedded in a hardware and virtual DCS by the use of preconfigured function block templates that provide generic mass, energy, and component balances. Kinetics for reactions, mass transfer coefficients for phase changes, charge balances for pH, and population balances for cells and crystals are added via preconfigured function block templates for common equations and methods. The user can provide custom calculations by writing to parameters allocated for this purpose. An actuator template offers stick-slip, backlash, and a rate limited second order plus dead time model for valve response. A control valve template accepts data points from a standard valve sizing catalog to provide an inherent flow characteristic. A sensor template introduces sensor dynamics, errors, and noise which are useful in preventing the simulations from becoming too quiet. These preconfigured composite templates form a library in the DCS. The user can use these library templates in the same graphical configuration environment for the control system. The embedded process models inherently run at the same realtime factor as the control system. The resulting "virtual plant" can be used to teach and study the interrelationship between process dynamics and system design. For example, a virtual plant was used to reduce the capital cost of a neutralization system by \$500K [17].

Key parameters of the dynamic process models can be adapted online by an innovative use of model predictive control (MPC). In cases implemented to date the "virtual plant" has a replication of the control system in the "actual plant" and an external or an embedded dynamic first principle process model running realtime. The "virtual plant" control system gets its set points from the "actual plant" control system so that the control systems are running at the same operating point. Fig. 12 shows the set up of a MPC for adaptation of the process model in the "virtual plant" and a MPC for optimization of the "actual plant" [15] [16].

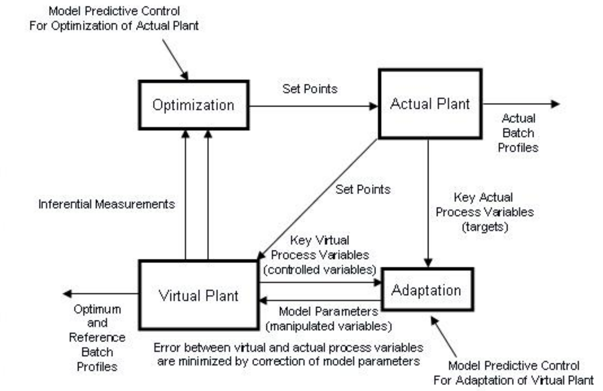


Fig. 12. Model predictive control can be used for online adaptation of the "Virtual Plant" to create inferential measurements for optimization of the "Actual Plant" [15 [16].

The MPC for optimization of the "actual plant" uses inferential measurements from the "virtual plant." For batch operations, these measurements are the rate of change (slope) of key composition profiles to provide bi-directional changes (positive and negative), self-regulation, and maximization of batch progression [15] [16].

The MPC for adaptation simultaneously manipulates key model parameters to match key variables such as uncontrolled compositions or manipulated flows between the "virtual plant" and the "actual plant." Applications to date include the adaptation of tray efficiencies of an external dynamic distillation model to match column overhead and bottom compositions in a pilot plant and adaptation of influent acid composition to match the reagent to feed ratio in a large intermediates plant's waste treatment system [18].

The identification of the dynamics of the experimental models and performance testing of the MPC used for adaptation and optimization can be done by running automated tests of the "virtual plant" offline by creating a second "virtual plant" acting as the "actual plant." Changes in process model parameters and disturbances are introduced for performance testing and exploring "what if' scenarios.

Process data from experiments and plants can be played back in a 'virtual plant" at extraordinarily high speeds for analysis and development of new algorithms. For example, months of historical data from the operation of industrial plants have been played back in a matter of minutes for the development of algorithms for online data analytics for batch processes and online identification process dynamics for adaptive control. This playback capability performed a key role testing and improving the algorithms for actual operating conditions. Huge amounts of process data can be rapidly used. The main limits to playback speed are the PC processor capability for code execution and DCS module execution time.

Most published advances in process analysis and control is based on simulation data. While this is a worthwhile first step, the use of actual plant data is essential because of the nonlinear and non-ideal behavior of processes, loops, sensors, and control valves. Processes often have unspecified set point changes, unknown disturbances, sluggish or oscillatory controller tuning, noisy or coated sensors, and limit cycles from control valve stick-slip or backlash. This playback feature of a virtual plant offers the opportunity to take advantage of the extensive historical plant data that is saved in a modern DCS in industry. Many companies would be willing to share this data and enter in a joint research effort with a university with the confidence that the technological advances are tested with their plant data. Furthermore, the implementation of prototypes in a university DCS facilitates the deployment to an industrial DCS due to the use of standards and common features.

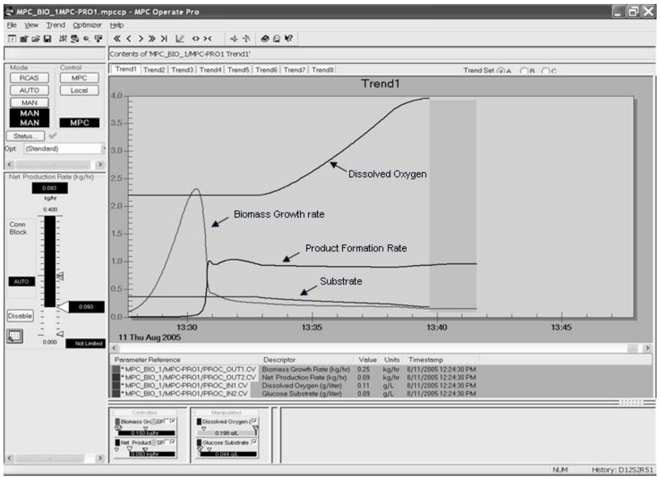
The "virtual plant" offers a low cost flexible, maintainable, and portable solution for taking innovations from concept to commercialization. The "virtual plant" can minimize but does not eliminate the need for deployment on an actual process. The "hardware DCS" is used in an industrial automation system to control unit operations in a research lab or pilot plant for further research and development.

The use of industrial instrumentation simplifies the I/O for a "hardware DCS" and provides more reliable, maintainable, and accurate measurements. Smart industrial instrumentation also facilitates the use and benchmarking of industrial versus university advances in online diagnostics. WirelessHART technology eliminates the cost and time for signal wiring and provides a portable measurement that can be readily moved to different experimental setups for unit operations.

The use of automation system hardware and process equipment is valuable as a learning experience for students with no industrial experience and no concept of a real transmitter, valve, and controller. Familiarity with the hardware, terminology, standards, and tools gives them an advantage in interviews and performance on the job.

XI BIOREACTOR EXAMPLES

The virtual plant has been recently used for control studies of bioreactors used in antibiotic, ethanol, human epidermal growth factor, and antibody production. For antibiotic production, control studies in a virtual plant showed MPC can reduce batch cycle time by more than 25%. The growth rate was controlled at a sustainable rate and the product formation rate was controlled at a peak rate by the manipulation of the set points for dissolved oxygen and substrate concentration as shown in Fig 13. The sustainable growth rate and peak formation rate were automatically captured by the use of the standard DCS feature for the set point to track the process variable in manual and a bumpless switch of the MPC to auto at the maximum formation rate.



Parameter Reference	Descriptor	Value	Units	Timestamp
*MPC_BIO_1/MPC-PRO1/PROC_OUT1.CV	Biomass Growth Rate (kg/hr)	0.25	kg/hr	8/11/2005 12:24:30 PM
*MPC_BIO_1/MPC-PRO1/PROC_OUT2.CV	Net Production Rate (kg/hr)	0.09	kg/hr	8/11/2005 12:24:30 PM
*MPC_BIO_1/MPC-PRO1/PROC_IN1.CV	Dissolved Oxygen (g/liter)	0.11	g/L	8/11/2005 12:24:30 PM
*MPC_BIO_1/MPC-PRO1/PROC_IN2.CV	Glucose Substrate (g/liter)	0.09	g/L	8/11/2005 12:24:30 PM

Fig. 13. A control study of a bioreactor in a virtual plant showed the potential to reduce batch cycle time by controlling biomass growth rate at a sustainable rate and the product formation at a peak rate [15] [16].

The mammalian cell bioreactor has the most complex model. Michaelis-Menten kinetics are used to model the effect of substrates and dissolved oxygen on cell growth rate and for product and by-product (lactate and ammonia) formation rates. Convenient cardinal kinetics are used to model the effect of pH and temperature to eliminate the extreme sensitivity and estimation difficulty of the exponential parameters for Nielsen-Villadsen pH kinetics (hydrogen ion concentrations for limitation and inhibition) and Arrhenius temperature kinetics (activation energies for growth and death). Bench top and a pilot plant bioreactors controlled by a DCS are being used in beta tests at companies and universities for the identification of kinetic parameters and the demonstration of advances in wireless devices, analyzer technologies, substrate control, and cell apoptosis control [19] [20]. Fig. 14 shows a single-use-bioreactor being used for these studies at one company. Results to date indicate WirelessHART pH transmitters have successfully eliminated spikes from ground loops, a straightforward enhancement to the PID and the use of feedforward control can eliminate oscillations from the sample delay of at-line analyzers, and many of the kinetic parameters can be estimated by batch-refeeds and semi-continuous runs.

For bioreactor control studies using the virtual plant, a combination of biological kinetic and media speedup factors are used to run batches at 500x realtime so that 20 day batch can be completed in less than an hour. These virtual batches can be played backed in a couple of minutes for testing the MPC adaptation of key kinetic parameters to match the growth, death, and formation rates computed from in-line and at-line analyzer results for biomass, cell viability, product, lactate, and ammonia concentrations.

Fig. 14. A single-use-bioreactor (SUB) and bench top reactors with wireless devices and new in-line and at-line analyzers and a lab optimized industrial DCS are being used for control studies in conjunction with a virtual plant.

XII CONCLUSION

Modern process control systems consist of an integrated set of software and hardware components that make it easy for student and researchers to define advanced batch and continuous control strategies that work with lab equipment or with a simulated process. Working in the DCS environment allows student to gain experience with measurement and control tools that conform to industry standards. When the DCS is connected to the university intranet, then students may remotely setup and monitor labs and experiments using their wireless laptops and workstations. The support DCS provides for collecting historical data makes it easy for student to retrieve data for further off-line analysis. External applications such as Matlab may be integrated into the DCS using OPC to support the development and testing of process models and new control techniques.

REFERENCES

[1] Macias-Hernandez, J. J., and Feliu, J. A., "Dynamic simulation and OPC," *Hydrocarbon Engineering,* vol. 8(9), 2003, pp. 53-58.

[2] OPC DA 3.00 Specification, "Data Access Automation Interface Standard" www.opcfoundation.com , 2003.

[3] PROFIBUS Organization, "Specification for PROFIBUS Device Description and Device Integration vol 3: FDT V1.1." Karlsruhe, Germany, Nov., 2000.

[4] *Kleines, H, Zwoll, K., and Sarkadi, J., "*Integration of Industrial Automation Equipment in Experiment Control Systems via PROFIBUS--Developments and Experiences at Forschungszentrum Julich", *IEEE Transactions on Nuclear Science Ns,* vol. 47, 2000, p 229.

[5] Diedrich, C., Russo, F., Winkel, L., Blevins, T., "Function Block Applications in Control Systems Based on IEC 61804", ISA Conference, Sept. 10-13th, Houston, Texas, 2001.

[6] Lian, F.-L., Moyne, J. R., and Tilbury, D. M., "Performance Evaluation of Control Networks: Ethernet, ControlNet, and DeviceNet," *IEEE Control Systems Magazine,* vol. 21(1), 2001, pp 66-83.,

[7] Sulzer, E. and Bertsch, M. "Design and Engineering of a Modern Process Control System**,"** *World cement*, vol. 28(10): 1997, p 72.,

[8] R.W. Lewis, "Programming Industrial Control Systems Using IEC 1131-3", IEE Publishing, ISBN: 0852969503, Oct., 1998.

[9] ISA-S5.3 "Graphic Symbols for Distributed Control/Shared Display Instrumentation, Logic, and Computer Systems - 1983", ISBN:0-07664-707-7-P.

[10] Blevins, T., McMillan, G, Wheatley, R, "The Benefits of Combining High Fidelity Process and Control System Simulation", in Proceedings of ISA Expr/2000, Chicago, Oct., 2000.

[11] Blevins, T., Ochoa, D., "Statistical Analysis Rides the Bus", *Intech*, Mar., 2000, pp. 48-59.

[12] Kuchle, D., "Multivariable Control on a Single-loop Budget", *Control Solutions*, Dec., 2001.

[13] Nisenfeld, A.E., "Batch Control: Practical Guides for Measurement and Control", ISA, 1996, ISBN: 1-55617-563-9.

[14] McMillan, G.K. and Cameron, R.A., *Models Unleashed - Virtual Plant and Model Predictive Control Applications*, International, Systems, and Automation Society (ISA), 2004.

[15] Boudreau, M.A. and McMillan, G.K., *New Directions in Bioprocess Modeling and Control*, International, Systems, and Automation Society (ISA), 2006.

[16] Boudreau, M.A., McMillan, G.K., and Wilson, G., "Maximizing PAT Benefits from Bioprocess Modeling and Control", *Pharmaceutical Technology Supplement: Information Technology Innovations in the Pharmaceutical Industry*, Nov., 2006.

[17] McMillan, G.K., Reedy, R.D., and Moulis, J.P., "Virtual Plant Provides Real Insights," *Chemical Processing*, Jan. 2009.

[18] McMillan, G.K. and Sowell, Mark. S., "Virtual Control of Real pH", *Control*, Nov., 2007.

[19] Boudreau, Michael and Benton, Trish, "Bioprocess Control - What the Next 15 Years Will Bring - Part 1", *Pharmaceutical Manufacturing*, vol. 7 (5), May, 2008.

[20] McMillan, G., Benten, T, Zhang, Y., and Boudreau, M., "PAT Tools for Accelerated Process Development and Improvement", *BioProcess International: Process Design Supplement*, Mar., 2008.