Process Control Design and Practice – A New Approach to Teaching Control to Chemical Engineers

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Abstract

Modern process plants in the chemical, oil, food, and pharmaceuticals industry are highly automated to meet modern standards of safety, productivity, quality, and environmental protection. Chemical plant operators today generally only "operate" by exception, stepping in when the automated system encounters a situation for which it is not prepared. As computers, sensors and automation have improved and decreased in price over the last 30-50 years, the process industries have invested heavily in automation. At the same time the one course that most chemical engineering undergraduates receive as part of the standard curriculum has hardly changed at all. Often titled "Process Dynamics and Control" it teaches Laplace domain analysis of simple time domain dynamic models, an introduction to linear control theory and its tools, with the culmination generally being a derivation of how to tune a single loop controller to achieve stable feedback control for a general dynamic model.

A newly minted chemical engineer working as a production engineer in a process unit will often be responsible for technical supervision of a process with hundreds of automated sensors, valves, motors and other I/O elements, including dozens of feedback loops. The stability of those loops will rarely be a concern (loop tuning can be taught empirically in an hour). A much greater challenge is to manage the complexity of this automated process. Why are all of these feedback loops present? How are sensors and control valves placed to absorb the available degrees of freedom? How do safety, quality, and environmental (SQ&E) goals translate to continuous and discrete constraints? How do you manage change and optimization in a plant operated by a control system? These are not primarily problems of analysis, but problems of design.

Process Control Design and Practice is a course that tackles the design problem of process automation. It teaches how feedback controllers are applied to manage the thermodynamic degrees of freedom to maintain a single state. The complexity of sequential logic design problems (batch plants, startup/shutdown in continuous units) is broken down into abstraction levels of unit control, equipment module control, and device control to allow modular design. Students learn to think algorithmically, breaking down complex sequences into actions and logical transitions. Batch recipes formulated by a chemist are translated to sequential unit recipes for implementation at production scale. SQ&E goals become logical statements that interpret sensor data and actuate valves, motors, or sequences. The student is taught to translate concepts recorded in process flow diagrams, piping and instrumentation diagrams, chemists' recipes, operator procedures, and accountants' ledgers into a control system design specification that can be executed by programmers and the people who build and maintain your process. By making students think and communicate about how chemical engineering unit operations function in time, this design course links engineering science theory to industrial practice while preparing students to practice engineering on automated processes. Whether as an elective or a replacement for the standard dynamics course, this course will better prepare chemical engineers for 21st century automated manufacturing.

Introduction

Modern process plants in the chemical, oil, food, and pharmaceuticals industry are highly automated to meet modern standards of safety, productivity, quality, and environmental protection. Process plant operators today generally only "operate" by exception, stepping in when the automated system encounters a situation for which it is not prepared. As computers, sensors and automation have improved and decreased in price over the last 30-50 years, the process industries have invested heavily in automation. The logic of having to meet the ever-escalating safety standard of "Recognized and Generally Accepted Good Engineering Practice" (REGAGEP) as part of OSHA Process Safety Management standards [1] means inexorable instrumentation and automation upgrades for old processes, and highly automated new processes. Environmental regulations, strict quality requirements and the constant drive to increase manpower productivity reinforce this trend; processes without modern automation do not survive. The displacement of the middle skill worker, who in the process industry was the floor operator responsible for one unit operation, has been happening gradually over the last 3-4 decades, replaced by a control room operator who interacts with a control system operating many units. Implicitly this has transferred the responsibility for control of units and processes from the operations staff to the engineering staff. An engineer wishing to build, modify, maintain, or optimize a modern process plant has to be able to understand not only the underlying unit operations that make up the process, but also to understand, specify, and communicate with the automation system operating and tying together those units.

At the same time the process industry was investing heavily in instrumentation, automation and control systems, the one course in process control that most chemical engineering undergraduates received as part of the standard curriculum has hardly changed at all. Often titled "Process Dynamics and Control" (PD&C) it teaches Laplace domain analysis of time domain dynamic models, an introduction to linear control theory and its tools, with the culmination generally being a derivation of how to tune a single loop controller to achieve stable feedback control for a general dynamic model with one input and one output. PD&C is a natural fit in the chemical engineering curriculum, analogous to courses in heat, mass and momentum transfer where differential equations describing transport phenomena (versions of the Navier-Stokes equation) and heat, mass and momentum conservation are solved to describe the transport phenomena that underlie the chemical unit operations used to transform matter into more useful forms. PD&C extends those solutions by removing the frequent assumption of steady state, and then proceeds to analyze the problem of maintaining a steady state using the mathematics of linear feedback control theory. All of these are courses on micro-phenomena; the findings from transport phenomena are then used to justify principles of design and operation of macro-phenomena such as reactors, distillation columns, absorbers/adsorbers, filters of various types, and mixers. Generally missing from these macro-phenomena courses is any discussion of the instruments, valves, feedback controllers and sequential logic needed to operate these units. The final capstone macro-phenomena course, usually called "Process Design" or "Plant Design", requires the students to tie together many unit operations to create a full process, which is modelled, sized, and costed. This course has little time to discuss how the simultaneous operation of many unit operations is to be coordinated by a supervisory control system.

“Assume steady state” is a normal part of any unit or process design, but that assumption is an admission that a major part of any actual design is not being addressed, the macro-phenomena of unit and plant control.

Electrical and Aeronautical/Aerospace engineers take several courses in control, fully exploring state space linear control theory; this applies well to the linear high speed control realms of electrical and aeronautical design. Control is central to senior level design in both fields. Mechanical engineers also learn the micro-phenomena of control but then extend it to macro-phenomena with all or part of a senior design course in factory automation [2]. Chemical Engineering is alone in the major disciplines in not incorporating automation design into the design education of seniors completing their bachelor’s degree. This is one of the causes of a persistent shortage of Process Control engineers with chemical engineering degrees in the process industries [3]. Many companies lack engineers who can bridge the communications gap between instrumentation and control engineers with electrical engineering backgrounds, and process engineers with chemical engineering backgrounds. Consultants are hired in to help bridge this gap, but those consultants are most often also electrical engineers with little expertise in process engineering. Too many startups are delayed by failures of the automation design. Too many plants are insufficiently automated, not from lack of access to capital, but from lack of expertise to successfully design and implement an automated process. It is not unusual to find expensive automation systems underused by operators for whom it is more trouble than assistance, and engineers who lack the training to improve a poor installed system. Chemical engineers need to be able to describe and design control strategies capable of automating their process design ambitions.

The design of process automation varies somewhat from industry to industry, just as reactors and distillation columns differ from pharmaceuticals to the food and beverage industry or to oil refining. But there are underlying principles to control and automation design, just as there are to reactor design or distillation design. A course teaching process automation design will teach students to ask and answer the following questions, and accomplish the implied teaching objectives:

1. How do we analyze the automation needs of a process?
2. How do we analyze the different objectives of a process design, including safety, environmental, quality and productivity? How are they evaluated and synthesized into a control strategy?
3. How do we evaluate what we can and can’t control, given the limits of mass and energy balances, chemistry and thermodynamics?
4. How do we classify objectives into one-sided vs. two-sided, discrete vs. continuous? What strategies do we synthesize to satisfy those objectives?
5. How do we analyze and translate a procedural task into sequential logic, either for a batch process or the startup/shutdown of a continuous process?
6. A process can involve hundreds of process automation devices. How should we analyze a system and synthesize abstraction levels to modularize and simplify the design of process automation?

7. What is the nature of computers? What are their strengths and weaknesses? What are human operator strengths and weaknesses? How do we synthesize automation strategies that utilize the strengths of both computers and operators?
8. How do we communicate control strategies effectively with people who program computers, other engineers, operators and managers? How should we document process automation?

The Vocabulary and Grammar of Design

All design courses teach engineers to speak a new language. Engineers don't build things; they design things for others to build. They don't operate machines or a process; they describe how others should operate them, and in the 21st century, the other in question is generally an electronic control system. So a vital part of teaching design is not only the creation of the design itself, but the means to communicate that design to the intended audience of operators, engineers, and programmers. There are several communications tools and concepts that a chemical engineer must master to communicate clearly about the design of an automation system. Conceptually, the language to describe a control system starts with the idea of states. Once that definition is clear, students can learn how the state is measured and manipulated. Comfortable with that idea, students can learn to describe chemical engineering objectives using the vocabulary of states.

Thermodynamic State

By the time students are ready take a process automation course (senior year), they should be familiar with the idea of a thermodynamic state, but it is vital to begin an automation design course with the ideas of state variables and degrees of freedom. Students will know the terms from previous classes, but the abstract concepts from Thermodynamics class will take on new significance when expressed in simple systems of liquids and gasses moving through pipes, tanks, and heat exchangers. The purpose of a control system is to fully specify the thermodynamic state of a process, either to hold that state constant, or to change that state in a safe and reproducible way. Continuous processes have states that change in space, but not in time (other than startup/shutdown). Batch processes have states that change in time, but not in space. Safety, quality and environmental objectives will be expressed in terms of safe/unsafe or in-spec/out-of-spec regions or points within the thermodynamic state space.

Students work through exercises where for various processes of growing complexity they determine what flows (degrees of freedom) need to be controlled to achieve a fully specified state for a system. Through examples they learn what it means to have an over-specified (too many objectives) or underspecified system. While in theory determining the number of degrees of freedom is a question of writing out the mass and energy balance, together with some stoichiometric and thermodynamic relations, this quickly becomes cumbersome for even a process with 4-5 degrees of freedom, much less a larger process with multiple reactors and columns that might have 20 degrees of freedom. There are heuristic methods which greatly simplifying specifying a design, which can then be checked to ensure that it is fully specified.

Equipment State

In addition to the process fluids, the various pieces of equipment also have states. Those states can be either continuous or discrete. Pumps and agitators are on or off (discrete); some also have a variable speed (continuous). Most valves are either fully open or closed, but control valves have a continuous position. Feedback control loops can either be maintaining a thermodynamic state variable at a setpoint (AUTO mode) or holding constant a controlled device (MANUAL mode). Students need to begin to think of the equipment state of a unit as a vector where the state of every device is specified. A control system will put a unit's equipment into a particular state to achieve the goal of the process fluids reaching a specified thermodynamic state. Sequential batch processes in particular are controlled by establishing an equipment state, then waiting for the process to reach a thermodynamic state before moving to the next equipment and thermodynamic state in a series of steps to accomplish the goals of the batch.

Hardware

Piping and Instrumentation Diagrams

The standard Chemical Engineering Process Design course stresses the creation and use of the Process Flow Diagram (PFD), as is appropriate for a course where students design processes and utilize process simulators. But the much more detailed Piping and Instrumentation Diagram (P&ID) will be the design drawing that they use every day when they go to work as an engineer. The P&ID, while still a schematic, shows the relative locations of all equipment, including vessels, columns, and exchangers. It shows all of the process and utility piping, pumps, valves, and documents the basic control strategy. A common complaint of employers is the unfamiliarity of new engineering graduates with this key communication tool. Much of the design work in this course will take the form of small P&ID diagrams, so students have to be introduced to this tool early on. The complexity of their diagrams will grow as the course progresses and they learn more. Use of a software drafting tool such as Microsoft Visio™ or Edraw Max™ with drag and drop tools can make project work quicker, but pencil and paper will suffice.

Measuring the Thermodynamic State – Sensors

What quantities can be measured to describe the thermodynamic state of a process stream?
How are temperature, pressure, flow, weight, and level measured?

It is important for engineers to understand what is possible in terms of process state measurement. Some measurements are easy and inexpensive, and should be used liberally, not only for process control and constraint monitoring, but also for troubleshooting, accounting, and process monitoring purposes. Other measurements (most composition measurements, for instance) require a sizeable investment of money and development time, lack reliability, and tend to need a good deal of ongoing maintenance. Students should learn enough of the underlying physics to be able to choose the measurement technology that is most appropriate for a given fluid and geometry, together with the relative precision and reliability of different sensor technologies. They perform design exercises where they place sensors on units to achieve process control and other goals.

Controlling the Thermodynamic State – Valves, Pumps, and Heat Exchangers

Pumps add energy to fluids in the form of pressure, which can be exploited as flow. Control valves subtract energy from fluids, subtracting pressure and limiting flow. Controlled utility flows through heat exchangers add or subtract heat to process fluids. A combination of those inputs are the tools for manipulating the state. While students understand this in terms of fluid mechanics and heat transfer, they need to wrap their minds around what it means to control an available degree of freedom, why adding a heat exchanger can create a degree of freedom, and why the conservation of mass and energy limit the number of valves, pumps and heat exchangers that can be usefully added to a process. An interesting discussion can be conducted on the virtues of variable speed pumps vs. control valves for controlling flow.

Computers and Electronics

Chemical engineers should be familiar with the idea that a control system is a network of computers that talk to each other, using some of the same protocols as the internet. What is a controller, an I/O card, an operator terminal, and how do they all talk? How does information from sensors become a variable ready for use within the system software? The objective is not to teach chemical engineers to be electronics technicians or programmers, but to enable them to converse knowledgeably with those experts. Most engineering students are at least partly aware of how the internet works; it's possible to teach the basic architecture of a control system by analogy to the internet.

Objectives and Control

There are a variety of different objectives that any control system is monitoring and trying to satisfy at any time. Some of them take the form of maintaining a thermodynamic state at a target, some combination of temperature, pressure and flow. For instance, maintain a constant purity in the distillate product of a distillation column by maintaining a constant pressure and a top vapor temperature at a target. In a continuous process there is generally a chain of mass balance controls to maintain steady state in the consecutive units of the process; these are also thermodynamic states (flows, levels, pressures) that must be held at target. These types of objectives call for the use of continuous feedback control loops.

Then there are objectives that reference the thermodynamic state but are one-sided. For instance, do not let the reactor pressure go above 45 psig to avoid triggering a pressure relief device. Do not allow a tank to overflow, or to empty below 5% level. Do not let the reactor jacket temperature rise more than 100˚C above the contents of the reactor to avoid cracking the reactor glass. Do not allow a measured stack composition rise above an EPA mandated level. Many safety and environmental goals are one-sided continuous goals. One sided goals lead to continuous constraint control.

Finally there are discrete objectives. If the rupture disk blows, stop the feed to the vessel. If the pump motor stops, close the block valve after the pump to prevent backflow. If the pump starts, open the block valve after the pump to allow flow. If the high level switch is triggered, block inlet flow to the tank. Discrete objectives call for the use of interlocks and permissives.

Continuous Feedback Control

In a course devoted to automation design, there is no time to delve into the mathematics of linear control theory; that's at least a second course worth of material (Mechanical, Electrical or Aeronautical Engineers spend 2-3 courses on control theory), and that introduction to control theory is Process Dynamics and Control (PD&C). If a student is truly interested in process control, I would strongly encourage them to take both PD&C and this automation course. That having been said, the practical knowledge of how a feedback controller functions, and how they are used in an industrial setting, can be imparted in a couple of lecture hours, although not with any real understanding of control theory. The student is left with a technician's understanding of controllers, adequate to use and design with them, but not a deep understanding.

The processes that are found in the process industries have hundreds of simple feedback loops, but few with dynamics that both a) difficult to control, and b) tackled well by linear control theory. It is useful for a chemical process control engineer to understand how to deal with processes with significant dead time using some form of model predictive control, and how to recognize and decouple loops with coupled dynamics, but that should be the end goal of a one term PD&C class; that can't be covered in a process automation design course. In this course, the student will learn that feedback controllers manipulate degrees of freedom to maintain a process at a desired thermodynamic state, where to place sensors and valves, and some empirical rules for controller implementation.

Continuous Constraint Control (One-sided Continuous Objectives)

In theory this becomes a multivariable control problem, but in practice the vast majority of one-sided objectives can be implemented by taking two continuous loops, one for the constraint objective, and one for a target or minimization objective, compare their outputs and send the maximum or minimum to the control device. While teaching how to build constraint controllers, the students can learn to use Function Block Diagram (FBD, see Figure 1 below) communication tool, which represent each sensor, valve, and controller as a block, with input points for parameter like setpoints. As control strategies grow in complexity beyond simple loops, it is a struggle to diagram them on a P&ID. The FBD is the standard way continuous controls are configured in modern DCS and PLC systems; the graphical representation of a control system as a set of object-oriented calculating blocks helps students understand the underlying structure of the process controller, with inputs, outputs, and intermediate calculating points.

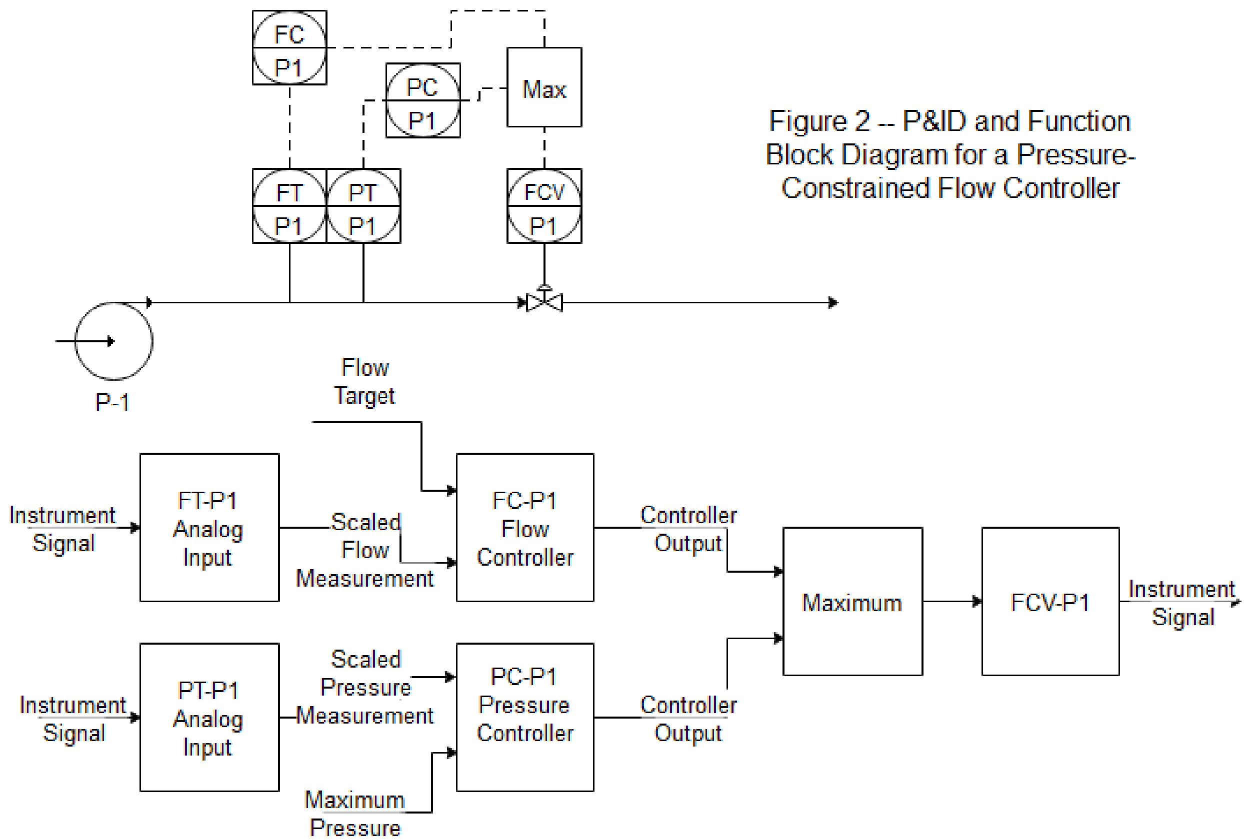

Figure 2 -- P&ID and Function Block Diagram for a Pressure-Constrained Flow Controller

Discrete Control (Interlocks and Permissives)

Discrete control objectives are written in the form:

If {Logical Expression using available state data} THEN {Control Action} AFTER {Delay}

A unit such as a reactor or a distillation column can have dozens of discrete objectives. Many of them are to shut down the unit if the process reaches an unsafe state and are quite simple. Others can be quite complex. For instance:

> A pump empties the distillate receiver on a distillation column; a control valve and level control loop tries to maintain a constant level of 50% in the receiver. The pump should never drain the receiver fully. The pump shouldn't run if the control valve is less than 10% open. When the column starts up, distillate only slowly starts to arrive at the receiver. When the column shuts down, the receiver should be drained to 5% full. Write the discrete logic to start and stop and pump, and turn the level controller from AUTO to MANUAL, such that the receiver's level will be controlled effectively without dead-heading the pump through startup, normal operation, and shutdown.

The important lesson for chemical engineers to learn is to plan through a scenario like that by mapping out all of the possible states (thermodynamic + equipment), deciding what the system should do in each state, and then writing a series of logical rules to carry out that logic. A student who can solve that problem will also have a new appreciation for the operation of receivers, pumps, and level control loops.

Sequential Control

Much of the process industry is operated in a batch rather than continuous manner. Even continuous processes have to start up and shut down in a controlled way. Most of the design of any control system deals with aspects of the process that occur sequentially, rather than continuously. A chemical engineer must be capable of taking a recipe written by a chemist based on lab experiments and translate that to a sequential procedure for an automated production scale reactor that typically will have 30 instruments and 20 valves of one sort of another. Even simple acts like charging a single raw material will require at least 10-20 steps, probably more if detecting and dealing with all possible failure modes are included.

To deal with this complexity, an engineer must master two skills. The first is formulating and documenting a procedure in detail, and then documenting that procedure using sequential logic. The Sequential Function Chart (SFC) is a graphical language for documenting sequential logic, defined in the open international standard IEC61131-3, and used by all control system manufacturers as an interface option. See Figure 1 for an example of an SFC which documents a batch recipe at a high level of abstraction, the level of a chemist recipe. Having students create SFCs teaches them to think algorithmically and with discipline, taking vague ideas of what needs to be accomplished (and vague recipes from a chemist) and translating them into actions and logical transitions, using parallel branches to convey simultaneous actions and branches with carefully written transitions to document contingent aspects of a procedure. This does not come naturally to most students, but a student who learns to write a clear, correct, and complete procedure in an SFC will also write better procedures of all sorts, an important skill for engineers.

The second skill to master is modularity. You deal with the complexity of 30 instruments and 20 valves by using modular layers of abstraction. The SFC in Figure 1 is an example of a Unit Recipe for a Unit Module (e.g. a batch reactor), which is not unlike a chemist's recipe, and forms an easily understood medium of communication with that chemist, the production staff or with other engineers. It is written in a vocabulary of phases such as ChargeA, ChargeB and TempControl. Phases are themselves parameterized sequential procedures each described by their own SFCs that may be a few steps to several pages in length. Phases complete one task and report completion and data back to the unit recipe. Phases examine sensor data, toggle valves and motors, and adjust the modes and targets of continuous feedback controllers in one Equipment Module. An Equipment Module is a group of Control Modules (sensors, valves, loops) which carry out a distinct task (e.g. charging, temperature or pressure control, discharge). An Equipment Module may have several phases (e.g. ChargeA and ChargeB for the Charge Module). These terms are from the ANSI/ISA-88 Batch Control standard [4]. Learning to break down the functions of a reactor or a distillation column into equipment modules and then writing phases, short parameterized procedures for those modules, is not only essential to automation design. It also teaches students a valuable approach for solving any complex problem, in particular the management of any large project.

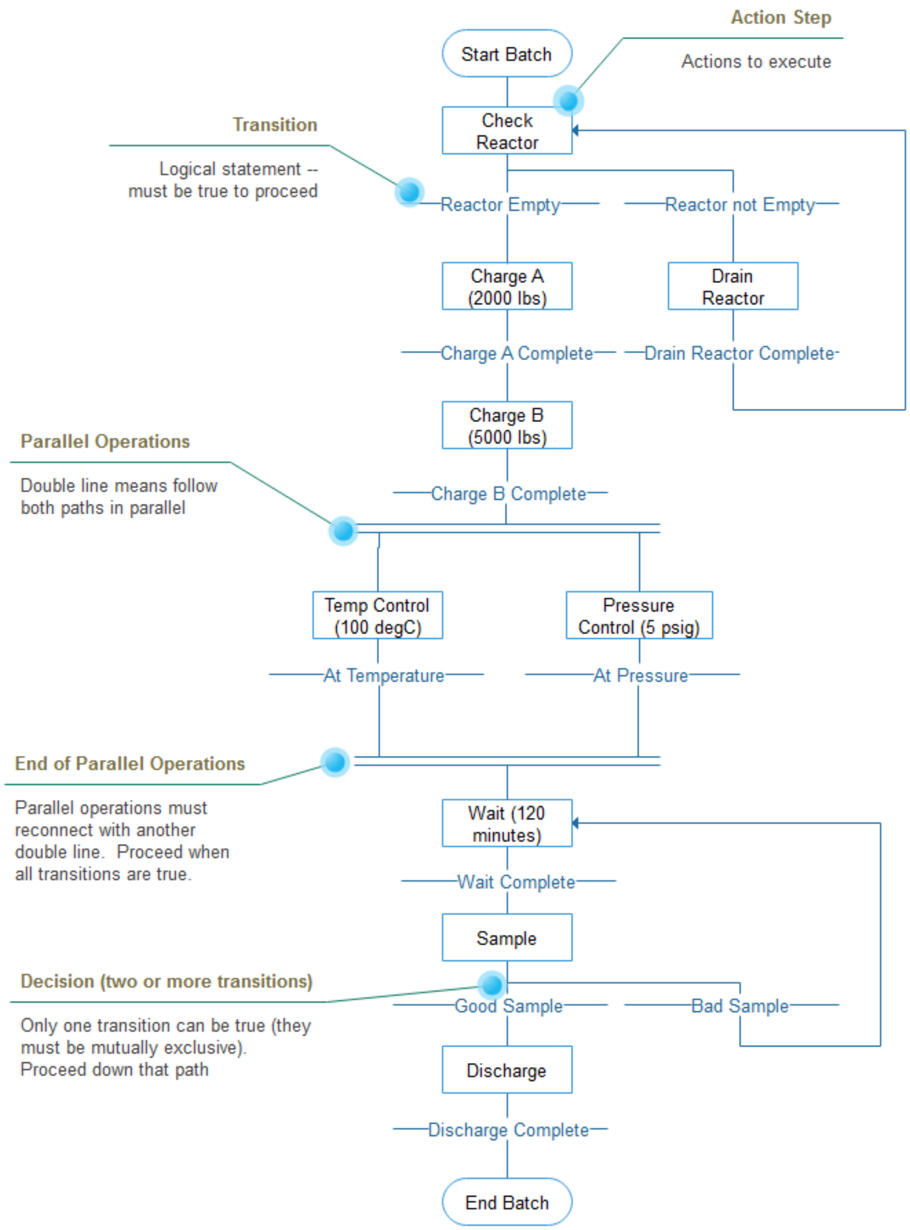

Figure 2 Sequential Function Chart

Documentation

Chemical engineers, even those who become Process Control specialists, are not going to spend their careers programming control systems; it would be a waste of their talents when other (lower-priced) professionals can be hired. To manage these professionals, chemical engineers need to practice writing a specification for a control system, generally called a Functional Specification. A poorly communicated automation design as much as a poor process or automation design are both likely to fail to meet safety, quality, and productivity goals; all design courses teach students to learn and speak a language. As further motivation, the Occupational Safety and Health Administration (OSHA) is starting to demand detailed documentation of control systems for Process Safety Management (PSM) regulated plants, an area where process plants are for the most part woefully deficient, so chemical engineers are likely to find themselves documenting automation designs. There are techniques for writing a clear and concise Functional Specification. Creating one for a term project exposes students to the correct form and exercises their report writing skills.

Human/Machine Interaction

Most automated systems are only partially automated. To fully automate any sufficiently complex task would require unacceptable levels of investment and engineering time, together with engineers who were omniscient in their ability to predict all possible futures. Chemical processes are very complex tasks, there are always limits to time and money, and even chemical engineers are rarely omniscient. In practice, a good design automates those things that benefit most from automation, and leaves certain tasks and responsibilities to the operator, while allowing that operator sufficient agency to be effective. Computers are very good at paying attention and following procedures precisely; operators less so. A well trained operator is very good at noticing and investigating abnormal operation before it becomes a crisis; he or she will often invent solutions to new problems. Computers only watch for the things they’re taught to watch for, and do the things they’re taught to do. The difficulty with automation design is to utilize the respective strengths of the operator and the computer system while avoiding their weaknesses. Operators should be given enough ability to take enough control to allow them to improvise solutions, or the plant will be inflexible and prone to down time. But the control system must prevent operators from taking actions that are dangerous or damaging to the plant. Every operating plant struggles with this balance. There are good standard practices to follow, but there are also grey areas, and differences from company to company. A discussion of this issue with examples to illustrate teaches students to look at multiple perspectives of people management and safety, in particular the perspective of the operator.

Conclusions

Chemical Engineering Process Control education has been limited to variations on the standard Process Dynamics and Control (PD&C) course for the last 50 years in most programs. PD&C fosters understanding of the inherent dynamics of chemical systems through the mathematical analysis of dynamic models and the application of linear control theory, but the practical value of the material learned is limited for the graduating professional entering industrial practice. That professional will find few problems worthy of dynamic modelling and analysis, but will instead find enormous automated process systems with thousands of instruments, valves, and motors trying to accomplish multiple safety, quality, productivity and environmental objectives. Understanding and learning to execute the design of process automation is a valuable and marketable skill for a graduate, but also a pedagogical opportunity to teach design techniques to deal with complexity, the discipline of algorithmic thinking, and a fresh perspective on various unit operations through examining how to control them and run them through their paces. Just as a capstone design course teaches students to combine many different elements of their professional education to synthesize a process design, a course in process automation forces students to examine what they have learned about reactors, columns, heat exchangers and pumps in order to synthesize systems and algorithms to operate them safely and automatically.

I believe that a design course in process automation is of equal or greater value to a PD&C course, particularly for the terminal graduate heading for professional employment. If offered as an alternative core course to PD&C, I am confident a majority would opt for process automation, as most seniors prefer design to mathematical analysis. Many employers seek the skills described in this paper. Those interested in pursuing Process Control as a specialty should take both, while those planning to enter graduate school will need the language of the Laplace domain and linear control theory garnered in PD&C if they plan to enter a research area where they might need to read process control research papers. The ideal place for this course in most chemical engineering department's syllabus is as a senior alternative to PD&C or a senior elective. Including this course as an option for graduate students (in many departments, a 500 level course) would attract interest from students pursuing a Master's degree while working as an engineer. In my experience working as a process control and process engineer, I encountered many engineers who wished they knew more about process control and automation. I plan to make teaching materials for this course available to other educators and students as a text book or a web page.

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