"Predicting the Future from the Past in Process Control"
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Let's start with the following question: How many cases do we have of academic research (this is the "past") with broad industrial success, in its operating practices, like DMC ?

The answer I would argue is, none. The reason is simple: The success of DMC did not depend on the "brilliance" of its algorithms. It resulted from the resolution of many practical problems that pave the road to success of any technology, and this cannot be normally done in a university.

So, jumping ahead to my bottom line,
"Current research in process control is not correlated to the future successes of industrial process control, but it does correlate very well to the preparation of the human resources that will create the future successes."
In this regard, academic research in process control did not cause, technologically, the extensive industrial applicability of DMC and by extension to any other practical manifestations of MPC. It did prepare people (students, practicing engineers), though, very well for this development.

I have structured my presentation in three parts, and decided to present a personalized account rather than attempting to describe every researchers "state" and "trends" over time:

- ☐ My "personal" state and trends in 1973-76 and how they related to the "Process Control" state and trends at the same period.
- ☐ <u>Predicting the Future:</u> The (Personally) "Missed" Signals in MPC
- ☐ <u>Other "Predictions" ?:</u>

A. My "Personal" State and "Trends" in 1973-76.

- ☐ 1970-71: <u>MS at McMaster:</u> Optimal Control Theory with State Estimation; Cam Crowe. Pontryagin's minimum principle etc. Essentially an exercise in applied math.
- ☐ 1971-74: <u>PhD Thesis at Univ. of Florida:</u> Non-Convex Optimization of Structured Systems; Duality Theory; Application to Process Synthesis.
- ☐ Educated with courses in Convexity theory; operations research; optimal control, etc.

    - Westerberg's puzzlement: Why so much fuss about Control ?
    - "Repeat Model Inversions with Corrections after each iteration"
- 1974-80: <u>University of Minnesota:</u> The Milieu of Process Control I found myself in when I started at Minnesota
    - Optimal estimation and optimal control; Lee, Markus
    - Mini-computers in data acquisition and control
    - Extensive discussions on: The Gap between Industrial and Academic work
        - The Three Critiques
            - "Critique of Chemical Process Control Theory", A. Foss, 1973
            - "Advance Control Practice in the Chemical Process Industry: A View from Industry", Lee-Weekman, 1976
            - "Design Concepts for process Control", Kestenbaum-Shinnar-Thau, 1976.
        - These 3 papers influenced my thinking a lot about process control and led to 2 research directions that I adopted:
            - Synthesis of control structures for chemical plants
            - Interaction between process design and process control
        - These 3 papers focused not on the "how to" but on the "what is", i.e. they focused on analyzing the characteristics of the process control problems, which in the authors' view were not being addressed by the prevailing control theories.
        - It is a historical fact that these 3 remarkable papers have been cited far less than many other inconsequential methodology-oriented papers; " solve effectively problems, no matter if the formulation of the problems is not the right one."
    - Let me spend a little time discussing the main points from these 3 papers

- The Critique by Foss:
    - Thesis: When it is stated, as it has been in more than one recent publication, that there is a wide gap between the theory of process control and its application, one is left with the unmistakable impression that those who conceive the theory are in some sense leagues ahead of those who would use it. That the contrary is the case is the thesis of this essay. Indeed, the theory of chemical process control has some rugged terrain to traverse before it meets the needs of those who would apply it.
    - Setting up the Problem Characteristics: The needs are intimately related to the problems, and the problems, as usual, wear a sometimes effective camouflage.
        - … And because the dynamics of a process are directly influenced by its design, the control system designer finds that his sphere of responsibility encompasses process design as well. Indeed, major contributions to effective control system performance often derive from perceptive and clever modifications of the process itself.
        - But such processes are not completely understood. … And it is well recognized that no amount of detailed study will ever replace all uncertainties with certainties. Rather, it is for the control system designer to recognize the significant uncertainties and to conceive controls that function effectively nonetheless.
        - … Yet the problems of control go still deeper. One is eventually forced to make both qualitative and quantitative decisions about the controlled system. One of the most important decisions concerns control objectives.
        - … It is by no means obvious how to achieve the best control. In addition to the possibility of making modifications to the process, there is the crucial step of conception (or invention) of the control system configuration. Which variables

should be measured, which inputs should be manipulated, and what links should be made between these two sets? This problem is considered by many to be the most important problem encountered by designers of chemical process control systems. It is certainly the most prevalent.

- Identifying the inadequacies of the prevailing control theories: I will not go into the details of this section, but instead focus on the suggestions of what the as yet (1973) unwritten theories should include.
  - Perhaps the central issue to be resolved by the new theories of chemical process control is the determination of control system structure.
  - … The representation of the process dynamics alone is a major task. Despite the considerable number of investigations of chemical process dynamics in recent years, there is still no practicable method for formulating low-order models of large multivariable processes, other than the hand wrought construction long of service to process control engineers.
  - … Associated with process modeling is the problem of state and parameter estimation. Estimates of measured and unmeasured states needed for control purposes require some sort of process model. But with the control structure unknown at the outset, the design of a state estimator becomes a much more difficult problem than in the past. The identity of the measured states will be unknown, and as it is certain that practicable estimators will not attempt to estimate all the states, the identity of those to be estimated will be unknown also.
- The Charge and Challenge to Academic Researchers: … There is more than a suspicion that the work of genius is needed here, for without it <u>the control configuration problem will likely remain in a primitive, hazily stated, and wholly unmanageable form</u>. Indeed, the same may be said for all aspects of the chemical process control problem. If not genius, then perception and the courage to tackle problems of an unfamiliar and unfriendly character. <u>The insidious trend of the past decade to seek mere translations of the control techniques arising in other fields has left the chemical engineering profession destitute of incisive investigation and substantial resolution of its own unique problems.</u> Instead only the elementary ideas should have been borne across the chasm separating spacecraft control from chemical process control and the seeds allowed to germinate in the virgin but unexplored valleys of the latter. That has not happened, but it must happen before practitioners can reasonably be expected to use the results of chemical process control theory. <u>And it must be made to happen by those with experience in process engineering</u>; there are few others who can perceive the problems and goals clearly and realistically. In fact, the chemical engineer is viewed by others to be in an extremely enviable position owing both to the wealth of control problems in his domain and his knowledge of processes. It would not be realistic to say, however, that he will be able to solve his problems singlehandedly; they are much too difficult. But if he can recognize those problems and respond with an imaginative attack and an inventive and pioneering spirit, there shall be some hope of narrowing the gap. <u>The gap is present indeed, but contrary to the views of many, it is the theoretician who must close it.</u>

- The Industrial View from Lee and Weekman.
- Reaffirming the “Gap”: Modem control methods have not made the expected impact on the control of chemical processes as originally anticipated in the first flush of enthusiasm. … The theoreticians argue that those involved in control applications are unable to understand the theory, while the practitioners argue that much of the theory does not apply to real processes. Nevertheless, all agree that there exists an unmistakable gap between theory and practice.
- Difficulties in Process Control Design:
  - ... The single most difficult problem to be overcome is understanding the process itself.
  - ...Our limited ability to measure state variables also aggravates the situation. Only very limited quantities, such as temperature, pressure, and flow rate, are readily measurable. … Besides, many unknown or uncharacterized disturbances persist.
  - ... Thus, critical information about disturbances are usually not known at the time of occurrence. This renders the task of characterizing disturbance and understanding the process dynamics very difficult. …
  - ... Small changes in the process design could influence the process dynamics profoundly. Thus, control configurations must be considered in the design of the process itself.

- **…** Rational design of control systems requires both steady state and dynamic information about the process. The more sophisticated the control system, the less the tolerance of inaccuracies in the model.
- **… conflicting control objectives …**

- Characteristics Manifesting the Needs of Industrial Practice
  - **Economic Incentives for Process Control**: In general, the overall value of the project is dominated not by the controllers' action but by the ability to predict the best operating point in terms of process variables. Economic incentives for advanced control may be considered to come from three different categories. …
  - **Varying Constraints**: Our experience in the petroleum industry also indicates that the optimal operating point commonly lies beyond the range of practical constraints. This probably occurs because of savings incorporated into the design due to capital cost considerations. Thus, a well-designed plant should operate at a constraint, or it is really overdesigned.
  - **Safety considerations:** … Anyone who has tried to implement advanced control schemes to an existing process plant quickly learns that he has to overcome several hurdles before he can make an attempt to try them. Some of these hurdles are of human nature, others technical. First of all, we must realize that safety and continuity of operation dominate the thinking of the operating staff.
  - **Process design decisions and their consequences:** … Another common revelation to the implementor of an advanced control scheme is that if the process design engineer had had the foresight to provide a certain control valve or heat exchanger, the whole advanced control project wouldn't have been necessary. … Too many current plant designs are performed on a steady state basis with little consideration, if any, given to the interconnected dynamic performance of the overall plant. One practical cure, which we have heard by the grapevine, is that the problem would not occur if the process designers were required to operate the plant for the first year. …
- Some New Directions:
  - … It (control theory) should not start from what skills the academicians happen to have or can borrow from other disciplines, but from the major needs of the end user. Indeed, the user and the theoretical developer should cooperate very closely: listening to each others problems, observing the process operation, and getting the user involved in the development effort.
  - … First, the process design and control design have to be integrated ***so*** that the dynamics and control configuration could be considered in the process design stage.
  - … **A** high priority should be assigned to new techniques designed to aid modeling of chemical processes.
  - … Methods for characterization of disturbance, to identify the process dynamics have to be improved.
  - … Finally, what we need is ease of implementation. There should be a unified, systematic procedure for resolving the difficulties encountered in the implementation of advanced control. **A** new control scheme has to be integrated smoothly with the operator as well as other controls of the plant.

- The Kestenbaum, Shinnar, Thau Analysis of the Process Control Problem and its Solution Methodologies
  - Design Criteria for a Controller
    - **Ability to Maintain the Controlled Variable at a Given Set-Point.** The first demand seems rather trivial, as this is the most obvious goal of process control. But this most essential requirement of process control is often the most difficult to fulfill as it creates mathematical difficulties for most of the optimization algorithms proposed thus far in the process control literature (Koppel, 1968) and we therefore would like to define it rather precisely.
    - **Set-Point Changes Should be Fast and Smooth.**
    - **Asymptotic Stability and Satisfactory Performance for a Wide Range of Frequencies.**
    - **The Controller Should be Designable with a Minimum of Information with Respect to the Nature of the Input and the Structure of the System.**
    - **The Controller Should be Insensitive to Change in System Parameters.**

        - **Excessive Control Actions Should be Avoided.**
    - Inadequacies of the optimal control theories
        - PID for a simple process superior to any optimization-based design methodology.

- HAVE SUBSEQUENT ACADEMIC RESEARCH AND DEVELOPMENTS IN PROCESS CONTROL ADDRESSED THE CONCERNS EXPRESSED IN THE 3 PAPERS?
    - Yes, to a significant extent:
        - The synthesis of the control structures became a high-profile goal.
            - Plant-wide control structures.
        - Control structure designs are introduced in eary process design.
        - IMC setup an effective framework for the "handling" of many controller design issue.
        - Led by DMC and followed by academic MPC-related research, many of the industrial concerns were explicitly addressed:
            - Selecting the control structure; inputs, outputs.
            - Using a "low-order" estimator for unknown disturbance effects and model uncertainties.
            - Handling of constraints and specially of changing constraints.
            - Addressing operational optimization explicitly, etc.
        - Integration of advanced control systems, such as the MPCs, with other legacy control and safety systems became a point of explicit interest.
    - No, on a number of issues:
        - Synthesis of plant-wide control configurations is a still a task with very spotty success and of limited practice.
        - Controller design considerations in process design are limited and spotty at best.
        - DMC and its successor MPC systems originally hid a number of critical factors, which have now started come to fore with significant implications.

- Signals I "Personally" Missed in Predicting the Future of Process Control
    - The 3 papers helped me significantly in getting a better handle on the "Problem Formulation" and defining research in two directions
        - Synthesis of control structures
        - Interaction of design and control
    - However, I missed the significance of certain academic papers and did not recognize it until much later:
        - A beautiful predictor of future MPC (from "Foundations of Optimal Control Theory", Lee and Markus, 1967)
          " … One technique for obtaining a feedback controller synthesis from knowledge of the open-loop controllers is to measure the current

control process state and then compute very rapidly for the open-loop control function. The first portion of this function is then used during the short time interval, after which a new measurement of the process state is made and a new open-loop control function is computed for this new measurement. The procedure is then repeated."

- ☐ The conceptual foundation of MPC (from: "The internal model principle for linear multivariable regulators"; Francis and Wonham; J. Appl. Math. and Optim., **2**(4), p. 380, 1975): An optimal regulator generates,
  - An inverse model of the dynamic system,
  - A direct dynamic model of external input.

- ☐ Summary
  - ■ In terms of technical impact that academic results have had in industrial practice: Correlation is low
  - ■ In terms of operational impact that academic research have had in industrial practice: Quite high
    - ☐ Well-trained people to "invent" the needed solutions and practical implementations
  - ■ The Most reliable path forward, focus on:
    - ☐ Systems theoretical fundamentals, not methodological solution details, and
    - ☐ Interesting industrial problems; the problems will reveal to the well-educated practitioners the path to new "inventions".
  - ■
- ☐