Process Control

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Process Control

K. J. Åström

Theme: Measurement Control Instrumentation and Communication (pneumatic).

Lectures

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The Power of Feedback

Feedback has some amazing properties, it can

- make a system insensitive to disturbances,
- make good systems from bad components,
- follow command signals
- stabilize an unstable system,
- create desired behavior, for example linear behavior from nonlinear components.

The major drawbacks are that

- feedback can cause instabilities
- sensor noise is fed into the system

Governors - Review

- Regulation of speed of of rotating machines
- Governors dedicated controllers that were built into the machines
- One device for sensing, control law and actuation
  Also separate actuators (servo motors) when large forces were required, which used feedback internally
- Design procedure based on
  Simplified models (Time constants)
  Dimension free variables and scaling
  Stability theory (Routh-Hurwitz) and rudimentary pole placement
  - Books Tolle 1905, Zhoukowskii 1909
- Emerging industry
- Europe in leading the development

Emerging Process Industry

- New industrial needs from emerging process and manufacturing industries: buildings, pulp and paper, petrochemical, pharmaceutical, food, brewery and distillery, glass and ceramics
- Desire to control many different quantities temperature, pressure, concentration, ...
- The role of sensors
  New sensors create opportunities for control
- Emerging companies for instrumentation and control
- Needs for display, sensing, control and actuation
- Automation of start and stop
- Marginal connection to development of governors
- Marginal theory development
- Leadership moved from Europe to USA

Organization

- Progress made by engineers in instrument companies. Little academic involvement
- Role of professional organizations and companies
- The journal *Instruments*
- 1936 The Process Industries Division of ASME formed Industrial Instruments and Regulators Committee in 1936. Ed Smith of Tagliabue driving force. Unified terminology, exchange of ideas and experiences.
- 1942 AAAS chose Instrumentation as the topic for a Gibson Conference
- 1945 Institute of Measurement and Control, London
- 1946 ISA formed as an organization for instrument technicians, plant operators. Open to people who did not have access to other professional societies.
- Instrumenttekniska föreningen, Stockholm 1961

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Instrumentation and Control

- Industrial needs for sensing, recording, control, actuation and display
- Development often driven by new sensors and actuators
- Measurement technology
- Emerging standards for communication 3–15 psi
- Control wide spread in mid 1920s
- Fraction of factory cost 0.4% (1920) to 1.4% in 1935. One third for controllers in 1923.
- More than 600 instrument companies in USA by mid 1930
- Instrument companies
- Instrument engineers
- Organizations ISA (Instrument Society of America ⇒ International Society for Automation)

Instrument Companies 1

- C. William Siemens and E. Werner Siemens London 1844, the chronometric governor which had integral action.
- Brown Instrument Company founded in mid 1800. Edward Brown invented a pyrometer for measuring temperature. Acquired by Honeywell 1934
- Taylor Instruments, George Taylor and David Kendall 1851. Thermometers and barometers.
- William Fisher constant pressure pump governor 1880
- Fisher Governor Company 1888 Marshaltown. Became part of Monsanto in 1969. Merged with GEC to form FisherControls International, 1979. Became Fisher-Rousemount in 1992, renamed Emerson Process Management 2001. (Delta V 1999)

Instrument Companies 2

- Butz Thermo-Electric Regulator Co 1885 reorganized in 1893 by Sweatt to become Sweatt's Minneapolis Heat Regulator Co..
- Honeywell Heating Specialty Co. (Mark C. Honeywell). Hot water systems for homes. Merged with Sweatts company in 1913
- Bristol Company 1894. Temperature controller 1903.Improved pressure indicator and recorder. Industrial Instrument Co 1908 in Foxboro. Changed to Foxboro Co in 1914. First multiple pen recorder 1915.
- 1899 Morris Leeds Company, joined with theoretical physicist Northrup to form Leeds & Northrup 1899. Precision instruments for labs; galvanometers, resistance boxes, industrial instrumentation 1920

Instrument Companies 3

- 1900 Tagliabue Co air-operated temperature controller
- 1903 Lynde Bradley and Stanton Allen formed Compression Rheostat Co, a forerunner of Allen-Bradley
- 1916 Bailey Meter Company, Erwin G. Bailey instruments for boiler operation
- George Kent, England boiler control
- Elliot Brothers, England boiler control
- Siemens, Germany boiler control
- Hagan Controls, supplier of boiler and combustion control, became Westinghouse Combustion Control and in 1990 Rosemount Control.
- 1937 Fisher & Porter, Philadelphia rotameters
- Much turbulence in 1980 and 1990.

The Swedish Scene

- Nordiska Armaturfabriken (NAF ⇒ Saab ⇒ Alfa Laval Automation) 1899 ⇒ Saab 1899 ⇒ Satt Control ⇒ ABB
- TA (Tour Andersson ⇒ TAC ⇒ Schneider) 1875
- Källe Regulator 1933
- Billman Regulator (⇒ Landis and Gyr ⇒ Siemens) 1929
- ASEA (⇒ ABB)
- AGA
- Alfa Laval Automation (⇒ Satt ⇒ ABB)
- ElektronLund Satt Control ⇒ ABB

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1. Introduction
2. The Industrial Scene
3. Pneumatics
4. Theory?
5. Tuning
6. More Recent Development
7. Summary

Theme: Measurement Control Instrumentation and Communication (pneumatic).

Pneumatics

Why?

- Actuation
- Signal transmission
- Safety - no electricity
- Advantages of standard
- Flexible and inexpensive

Components and and an idea (Force Feedback)

- Flapper valve
- Volumes, needle valves, and bellows
- Amplifiers
- Force feedback

  Good subsystems from bad components
  Shaping behavior: Creating linear behavior

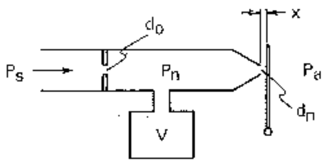
The Soul of a Pneumatic Controller

- Flapper valve

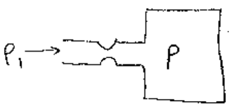
  1885 Johnson, flapper nozzle
  1914 E. H. Bristol used it in controllers
- Pneumatic amplifier
- Bellows
- Volumes and restrictions
- Feedback makes a linear system of strongly nonlinear components
- Foxboro Stabilog Mason and Frymoyer
- The principle of force balance

The Components

The flapper valve - position to pressure transducer



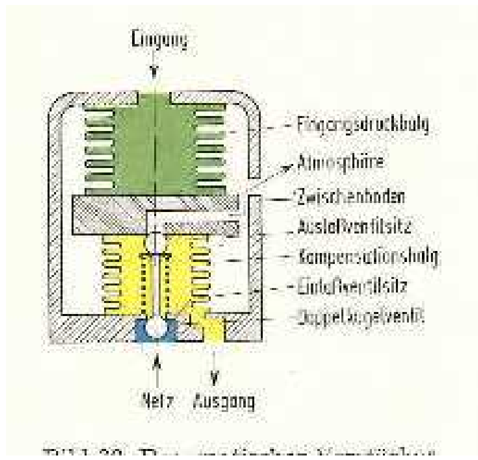
Volume with a restriction (calibrated needle valve)



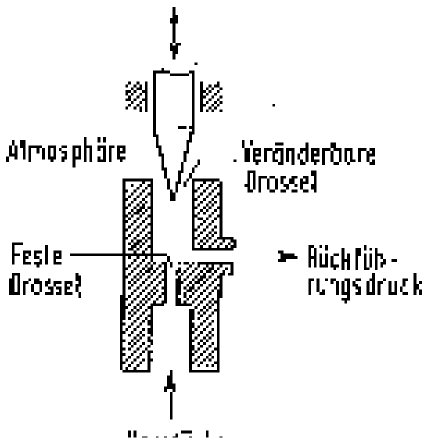
$$T\frac{dp}{dt} = p_i - p$$

$$G(s) = \frac{1}{1+sT}$$

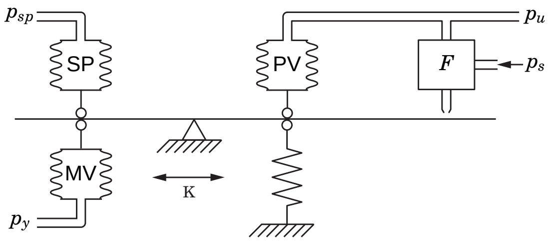
The Pneumatic Amplifier



Gain Reducer



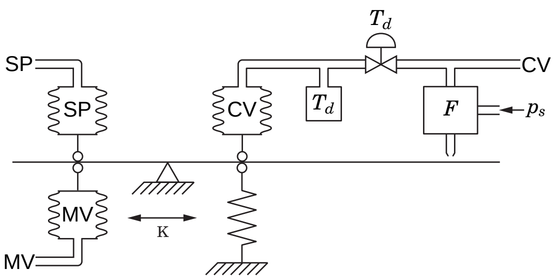
Proportional Control



Assuming that the gain of the flapper valve is so high that the bar is always horizontal it follows from a **force balance** that

$$P_{sp} - P_y = P_u$$

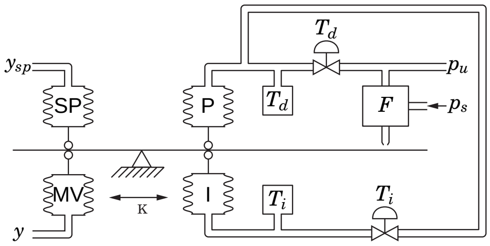
Proportional and Derivative Control



Assuming that the gain of the flapper valve is so high that the bar is always horisontal it follows from a **force balance** that

$$P_{sp} - P_y = \frac{1}{1+sT}P_u, \qquad P_u = (1+sT_d)(P_{sp} - P_y)$$

PID Control

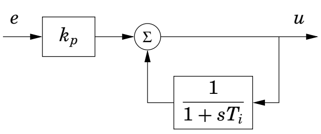


The **force balance principle**: $E = P_{sp} - P_y$

$$E = \left(1 - \frac{1}{1+sT_i}\right)\frac{1}{1+sT_d}P_u, \qquad P_u = \frac{(1+sT_i)(1+sT_d)}{sT_i}E$$

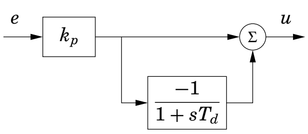
Block Diagrams

Integral action by positive feedback



$$u = k_p\left(1 + \tfrac{1}{1+T_i}\right)e = \tfrac{1+sT_i}{sT_i}e$$

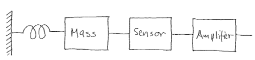
Derivative action by parallel connection of fast and- slow

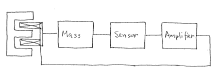


$$1 - e^{-sT} \approx 1 - \tfrac{1}{1+sT} = \tfrac{sT}{1+sT}$$

Force Feedback

- Idea with tremendous impact
- Game changer in design of sensors actuators and controllers
- Good example of: good systems from bad components





Open loop, all components matter

Bandwidth $\omega_b = \sqrt{k/m}$

Sensitivity = k_a/k

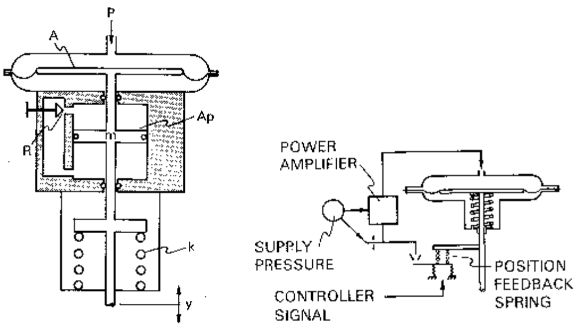
Invariant $\omega_b^2 S = k_a/m$

Closed loop, actuator only critical element

Bandwidth depends on feedback system

Error signal also useful!

Integration with Valves



I. M. Stein Leeds & Northrup

“The operator automatically observes not only the momentary condition and the direction of change of that condition, but observes also the rate of change of that condition with respect to time (the first derivative) and the rate of change of the rate of change (the second derivative). These observations are very essential to close regulation, particularly in processes involving appreciable time lag.”

Commentary:

- Compare Smith predictor
- Importance of process input

Derivative Action

- 1930 Leeds & Northrup anticipating controller
- 1931 Bristol company degree-splitting anticipation
- 1931 Ralph Clarridge at Taylor used pre-act
  - Manufacturing of viscose rayon
  - Large lags in thermocouple
  - Difficult to obtain high gain
  - Large off-sets
  - Integral action did not help
  - Very good results with pre-act
- 1939 Taylor Fulscope a PID controller
- Not aware of earlier work on Governors

Quote from Interview with Ziegler

“Foxboro came out with their Model 40 about 1934-1935. It was probably the first proportional plus reset recorder/controller. The reset action was caused by spools of capillary which had to be changed for different reset rates.”

“Someone in the research department (Ralph Clarridge) was tinkering with Fulscopes and somehow had got a restriction in the feedback line to the capsule that made the follow-up in the bellows. He noted that this gave a ‘kicking’ action to the output. They tried this on the rayon shredders and it gave perfect control on the temperature. The action was dubbed ‘Pre-Act’ and was found to help the control in other difficult applications, like refinery stills. the Pre-Act was the first derivative control and was incorporated into the Model 56R.”

Commentary

- Notice work by Stodola!

From Interview with Ziegler

“The Pre-Act was not too popular, but I insisted in getting a more stable version of it incorporated in the Fulscope 100. ... Bill Vogt designed the reproducible needle valves for setting reset rate and pre-act time. This was the very first proportional plus reset plus derivative control integrated in one unit.

What was the market reaction?: Enthusiastic as hell! We knocked our prime competitor right out of major chemical plants, such as Dow and Monsanto. They thought it was such a wonderful mechanism with responses labeled with calibrated units. ... It had

- Settings for sensitivity, reset and preact. No other controller had this.
- Any combination, P, PI, PD, PID or on-off
- Calibrated dials
- Continuous wide ranges

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Process Control Theory

- Little impact on engineering practice
- Difficulties
  - Industrial structure (Uppfinnarjocke)
  - Complex behavior, time delays,
  - Understanding process dynamics
- Simulation
- Actors
  - Callender and Stevenson ICI
  - Hartree and Porter U Manchester
  - Ivanoff Kent Instruments
  - Mason and Philbrick Foxboro
  - Bristol and Peters Leeds & Northrup
  - Ziegler and Nichols Taylor
  - Spitzglass Tagliabue
  - Grebe Dow
  - Mitereff
- Organizations ASME and ISA

Ivanoff

Theoretical foundations of automatic regulation of temperature. Institute of Fuel **7** (1934) 117-130.

Ivanoff 1933: “In spite of the wide and ever-increasing application of automatic supervision in engineering, the science of automatic regulation of temperature is at present in the anomolous position of having erected a vast practical edifice on negligible theoretical foundation.”

- Used arguments based on frequency response to understand temperature control loops
- Primitive understanding of stability condition: loop gain less than one at ω_{180}
- Found that with proportional feedback loop gain must be less than 23.1. See Bennet page 51. Explain!

Mitereff

Principles underlying the rational solution of control problems. Trans ASME **57** (1935), 159-163.

Automatic control problems are solved at present by purely empirical methods and after installation the usual cut-ant-try method of adjustment is very tedious and unreliable.

Systematic characterization of controllers

1. $u = k\int edt$
2. $u = ke$
3. $u = k_1 e + k_2 \int edt$
4. $u + k_2 \frac{du}{dt} = k_1 e$
5. etc

Discussions of paper referred to Routh's stability criterion

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John G. Ziegler on Tuning

I did not know how to set this new controller and I realized that we had to get some way of determining the controller settings rather than cut-and-try. I was out on a still in a chemical plant and it was almost a life's work getting the settings. I finally got it stable, but I wasn't sure I had the right setting. We had a unit in our factory demonstration room which consisted of a series of tanks and capillaries to simulate a multi capacity system for a fairly typical process to control pressure.

Model Based Design (MBD) or Tuning

- Tuning was originally done by trial and error
- Moderate adjustment possibilities in early controllers
- J. G. Ziegler and N. B. Nichols Optimum Settings for Automatic Controllers. Trans. ASME **64** (1942) 759–768
- Develop mathematical model by simple experiment $(a,\ L)$ or $(k_c,\ T_c)$
- Apply some design method to obtain controller parameters
- Simple design rules $(a,\ L) \Rightarrow (k_p, T_i, T_d)$
- Set the parameters
- Adjustment rules - Tuning tables
- Develop of tuning rules interactive online

Use of Simulation

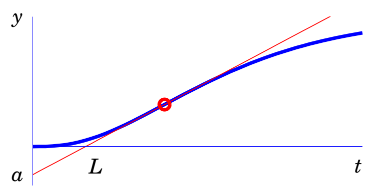
- Controller components used as simulator
- The Differential Analyzer
  - Little short term impact because differential analyzers were not widely available
  - Very large long term impact. Chemical companies became big users of analog computing
- 1935 Callender Hartree and Porter: Time lag in control system. Phil. Trans. Roy. Soc. **235** (1935-36), 415-444

$$u = k_1 e + k_2 \int edt + k_3 \frac{de}{dt}, \qquad T\frac{d(t)}{dt} + e(t) = u(t-T)$$

- Mason and Philbrick at Foxboro
- Ziegler and Nichols: Optimum settings for automatic controllers. Trans ASME **64** (1942) 759-768.

Ziegler-Nichols Step Response Method

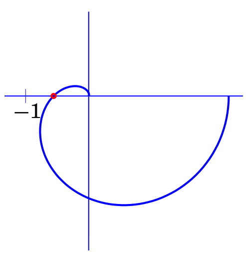
- Switch controller to manual.
- Wait for steady state.
- Make a step in the control variable.
- Log process output only and normalize the curve so that it corresponds to a unit step. Don't wait for steady state!
- Determine intercepts of tangent with steepest slope i.e. parameters a and L.



- Controller parameters are obtained from a table.

Ziegler-Nichols Frequency Response Methods

- Switch the controller to pure proportional.
- Adjust the gain so that the closed loop system is at the stability boundary.
- Determine the critical gain k_c and the period T_c of the oscillation.
- Suitable controller parameters are obtained from a table.



Ziegler-Nichols Tables

Step response

Reg.	k	T_i	T_d	T_p
P	$0.5k_c$			T_c
PI	$0.4k_c$	$0.8T_c$		$1.4T_c$
PID	$0.6k_c$	$0.5T_c$	$0.125T_c$	$0.85T_c$

Frequency response

Reg.	k	T_i	T_d	T_p
P	$0.5k_c$			T_c
PI	$0.4k_c$	$0.8T_c$		$1.4T_c$
PID	$0.6k_c$	$0.5T_c$	$0.125T_c$	$0.85T_c$

Quarter Amplitude Damping

Nick came to Taylor in the research department about the time the Model 100R was developed. I was playing on this analog simulator trying to figure out what determined the sensitivity, the reset rate and the pre-act time.

...

It turned out that when you set the proportional to about half of what caused the ultimate sensitivity, you would have about 25% amplitude ratio. So that is what we said - get an ultimate sensitivity and note the period. Any moron can do that. Then set the reset rate at one over the period and set the pre-act time to 1/6 or 1/8 of the period.

...

Nick wanted to use a 37% decay for some mathematical reason, but I insisted on the 25 % because it was very easy for someone to see that the second wave is half as big as the first wave.

Use of Simulation

Nick was cranking lut these curves for me for a lot of different processes. ... To speed it up. Nick rented the differential analyzer at MIT and got into discussions with people at MIT on fire control. They were having trouble keeping the systems stable, and Nick believed that even though their math was correct, there was another little time constant they were missing in the loop somewhere. He guessed it was the compressibility of the hydraulic fluid, which they denied. He convinced them to use Taylors pre-act, or derivative action, and when they put it in, the guns were stable.

As a result of all this, they asked him to come to the Radiation Lab at MIT to help win World War II. Taylor would not give him a leave of absence so he left. Lessons learned!

Assessment of Ziegler-Nichols Methods

- Published in 1942 in Trans. ASME 64(1942)759–768.
- Tremendously influential
- The beginning of process control
- Slight modifications used extensively by controller manufacturers and process engineers
- Uses too little process information: only 2 parameters
- Substantial improvements can be obtained with modified rules based on 3 parameters
- Basic design principle quarter amplitude damping is not robust, gives closed loop systems with too high sensitivity ($M_s > 3$) and too poor damping ($\zeta \approx 0.2$)
- What information is required to tune a PID controller?

The FOTD Model

$$P(s) = \frac{K}{1+sT}e^{-sL}, \qquad \tau = \frac{L}{L+T}$$

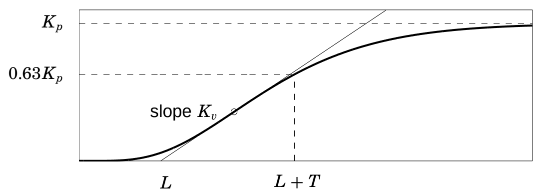
- Simple useful model extensively used in process control to approximate processes with monotone step responses
- Performance is fundamentally limited by L
- *Apparent dead time* L
- *Apparent lag or apparent time constant* T
- Relative time delay $\tau \le 1$
- Lag dominated dynamics τ small
- Balanced dynamics τ around 0.5
- Delay dominated dynamics τ close to one

Improved Tuning Rules

- Process information needed
- Pick a test batch of representative systems
- Choose design criteria maximize performance IAE subject to robustness constraints on M_s and M_t
- Use optimization methods to find controller parameters
- Explore how they correlate with process features
- What process features should be chosen?
- Has been executed for process control applications. These systems typically have essentially monotone step response
- Work on oscillatory systems in progress

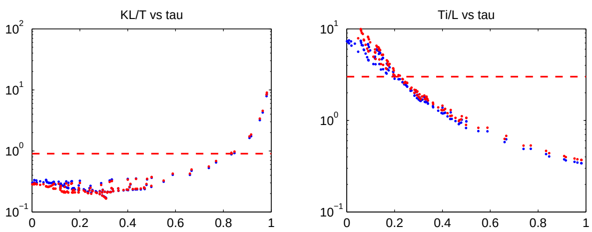
Improved Tuning Rules

Features of the Step Response



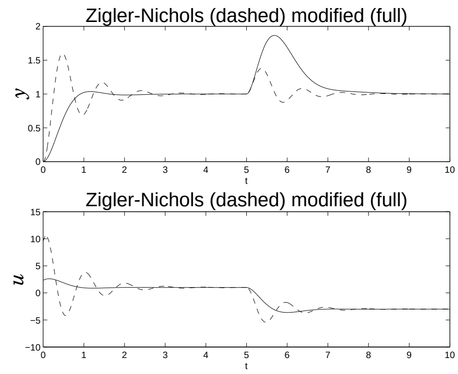
- Three parameters: K_p, ($K_v = K_p/T$, $a = K_vL$) L, and T
- Processes with integration included

Improved Tuning Rules

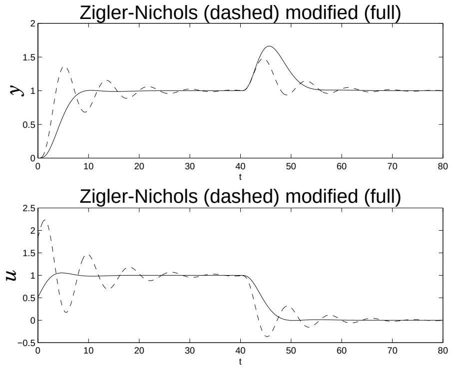


Ziegler-Nichols dashed red

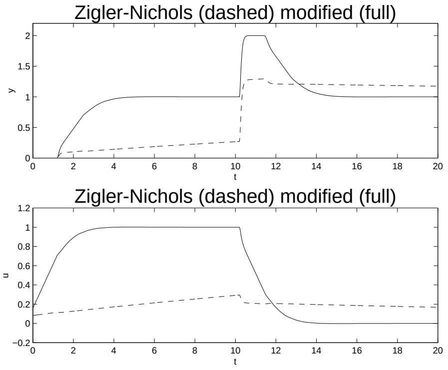
PI Lag Dominated Dynamics $L << T$



PI Balanced Process Dynamics $L \approx T$



PI Delay Dominated Dynamics $L >> T$



Process and Control Design

The chronology in process design is evidently wrong. Nowadays an engineer first designs his equipment so that it will be capable of performing its intended function at the normal throughput rate ... The control engineer ... is then told to put on a controller capable of maintaining static equilibrium for which the apparatus was designed. ... When the plant is started, however, it may be belatedly discovered that ... the control results are not within the desired tolerance. A long expensive process of 'cut-ant-try' is then begun in order to make the equipment work ... [then it is realized that] some factor in the equipment design was neglected. ... The missing characteristic can be called 'controllability', the ability of the process to achieve and maintain the desired equilibrium value.

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Dramatic Technology Changes

- Many opportunities in technology shifts
- Controllers
  - Pneumatics development as late as 1960
  - Electronic controllers
  - Computer control both for local controllers and systems
  - Automatic tuning
- Logic and sequencing
  - PLC
- Communication
  - Electric 4-20 mA
  - Wireless
- Instruments and sensors
  - Gamma rays for thickness measurement, infrared for moisture, spectroscopy, NIR
- Theory
  - University education
  - Research groups in companies
- Standards

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Summary

- Wide range of applications
  - Regulation of many different variables
  - Automation of start up and shut down
- Separation of sensing, actuation and control laws
  - Longevity of the pneumatic inheritance: structure and parameters (old technology in new clothes)
- Better freedom in implementing controllers
- Standardization of communication and interfaces pneumatic 3-15 psi
  - Centralized control rooms (relay and control cabinets)
  - Decentralized control with centralized displays
- Marginal theory development
- Extensive development of tuning and FOTD model
- Extensive industrialization control companies
- Leadership moved from Europe to the US

References

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