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REFLECTIONS ON THEORY AND PRACTICE OF AUTOMATIC CONTROL

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26T9 is a plenary talk presented at the 17th IEEE Decision and Control Conference at San Diego, January 10-12, 1979. Models and modeling is one major theme of the paper. The different roles of models in frequency domain and state space theories are discussed. The reason why simple models sometimes work so well is also covered as well as some issues in modeling of large systems. Computer aided design is the second major theme of the paper. It is argued that suitable computer aided design tools is a cost effective way to package theory. Examples from CAD packages developed at Lund are given. More complex regulators is the third theme of the paper. The substantial advances in LSI circuits certainly make more complex regulators feasible from the hardware point of view. The specific examples discussed include regulators which mix logic with ordinary control algorithms and adaptive controllers. The paper ends with some personal opinions on some major trends.

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# REFLECTIONS ON THEORY AND PRACTICE OF AUTOMATIC CONTROL

K. J. ÅSTRÖM



## 1. INTRODUCTION

BACKGROUND

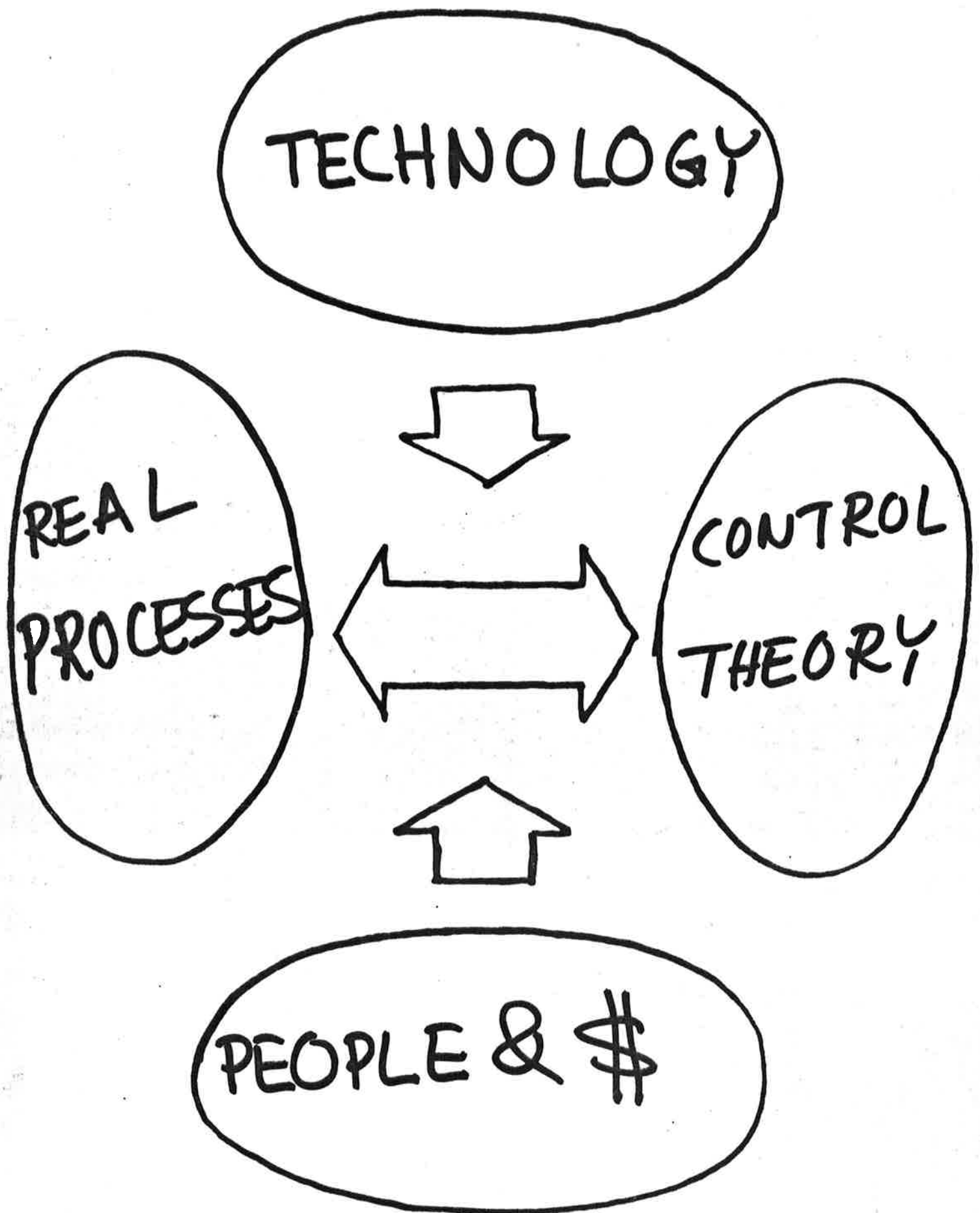
HEDGING

## 2. MODELS AND MODELING

## 3. COMPUTER AIDED DESIGN

## 4. MORE COMPLICATED REGULATORS

## 5. CONCLUSIONS



# REFLECTIONS ON THEORY AND PRACTICE OF AUTOMATIC CONTROL

## 1. INTRODUCTION



## 2. MODELS AND MODELING

ROLES OF MODELS IN CLASSICAL AND STATE SPACE THEORY

WHY DO SIMPLE MODELS WORK SO WELL?

HIERARCHY OF MODELS

MODELING OF LARGE SYSTEMS

## 3. COMPUTER AIDED DESIGN

## 4. MORE COMPLICATED REGULATORS

## 5. CONCLUSIONS

## THE ROLES OF MODELS IN CONTROL SYSTEM DESIGN

### CLASSICAL

PROCEDURE: FIX REGULATOR COMPLEXITY (PI, LEAD LAG, ETC).  
INVESTIGATE IF A VARIETY OF SPECIFICATIONS CAN BE SATISFIED.  
IF NOT, INCREASE REGULATOR COMPLEXITY.

DESIGN PARAMETERS: REGULATOR COMPLEXITY AND PARAMETERS.

MODEL: RESULTS ARE BETTER IF MODEL MORE ACCURATE. LITTLE  
PENALTY ON MODEL COMPLEXITY.

### MODERN

PROCEDURE: CHOOSE MODEL AND CRITERIA. APPLY DESIGN PROCEDURE.  
CHECK SPECIFICATIONS WHICH ARE NOT DIRECTLY GIVEN BY CRITERIA.  
ALTER MODEL AND CRITERIA.

DESIGN PARAMETERS: CRITERIA AND MODEL.

MODEL: THE REGULATOR COMPLEXITY IS UNIQUELY GIVEN BY MODEL  
COMPLEXITY. HENCE LARGE PENALTY ON COMPLEX MODEL.

### COMMENT

1. JET ENGINE MULTIVARIABLE DESIGN COMPETITION.
2. OFTEN QUOTED CRITICISM AGAINST LQG: "A KALMAN FILTER  
FOLLOWED BY A STATE FEEDBACK  $U = -L\hat{X}$  CARRIES WITH IT,  
HOWEVER, THE PENALTY OF MAKING THE COMPENSATOR AT LEAST  
EQUAL IN ORDER TO THE PROCESS MODEL, WHICH WILL NOT BE  
ATTRACTIVE FOR MOST INDUSTRIAL APPLICATIONS."

WHY DO SIMPLE MODELS WORK SO WELL  
FOR CONTROL SYSTEM DESIGN ?

AN UNEXPLOITED BUT INTERESTING PROBLEM AREA

- REQUIRES SYSTEMATIC APPROACH TO DESIGN
- RELATED TO SINGULAR PERTURBATIONS
- STATE SPACE NOT NECESSARILY THE RIGHT FRAMEWORK

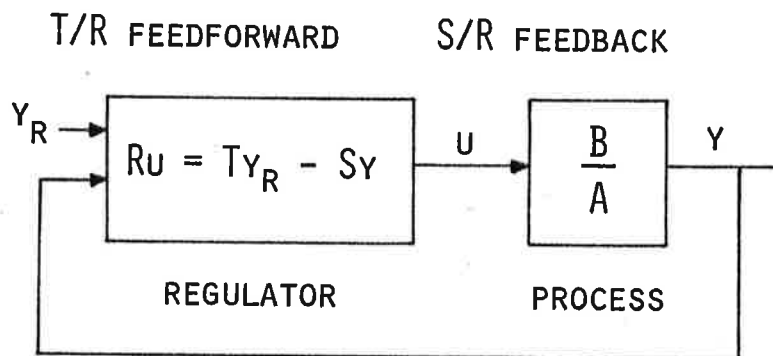
AN EXAMPLE

## POLE-PLACEMENT DESIGN

PROCESS:  $Y = \frac{B}{A} U$

DESIRED:  $Y = \frac{Q}{P} Y_R$

REGULATOR STRUCTURE:



THEOREM:

CONSIDER A REGULATOR OBTAINED BY APPLYING POLE-PLACEMENT DESIGN TO THE STABLE MODEL  $G = B/A$  WITH THE SPECIFICATION THAT THE CLOSED LOOP TRANSFER FUNCTION SHOULD BE  $G_D = Q/P$ . LET THE REGULATOR CONTROL A STABLE SYSTEM WITH THE PULSE TRANSFER FUNCTION  $G_0 = B_0/A_0$ . THE CLOSED LOOP SYSTEM IS THEN STABLE IF

$$|G - G_0| < \left| \frac{BPT}{AQS} \right| = \left| \frac{G}{G_D} \right| \cdot \left| \frac{G_{FF}}{G_{FB}} \right|$$

ON THE UNIT CIRCLE AND AT  $Z = \infty$ .

## MODELING OF LARGE SYSTEMS

### DESIRABLE FEATURES

- MODEL SHOULD BE EASY TO WRITE, CHECK, AND MODIFY.
- MODEL MANIPULATIONS SHOULD BE AUTOMATED.
- PROPERTIES OF MODEL SHOULD BE EASY TO FIND  
(SIMULATION, ANALYSIS, LINEARIZATION, ...)

### PROCEDURE

- CUT SYSTEM INTO SUBSYSTEMS.
- WRITE BALANCE EQUATIONS (MASS, MOMENTUM, ENERGY) AND CONSTITUTIVE EQUATIONS.
- DESCRIBE INTERCONNECTIONS HIERARCHICALLY.
- LET THE COMPUTER DO THE REST (COMPUTE STEADY STATE, GENERATE CODE FOR SIMULATION, LINEARIZATION ETC).

## EXAMPLE DYMOLA

H. ELMQVIST: A STRUCTURED MODEL LANGUAGE FOR  
LARGE CONTINUOUS SYSTEMS.

PHD DISSERTATION, LUND, MAY 1978.

LANGUAGE TRANSLATOR FOR OPERATING ON THE MODEL.  
SOLVE FOR STEADY STATE OR  $dx/dt$ , FORMULA MANIPULATION  
ETC.

EXAMPLE: MODEL OF A DRUMBOILER TURBINE

ORIGINAL DOCUMENTATION IS A 60 PAGE REPORT + STEAM TABLES.  
DYMOLA DESCRIPTION REQUIRES 9 PAGES OF CODE + STEAM TABLES !



MODEL POWERSTATION

SUBMODEL DRUMSYST

SUBMODEL (SUPERHEATER) SUPERH1, SUPERH2, SUPERH3

SUBMODEL CONTROLVALVE

SUBMODEL LPTURB

·  
·  
·

CONNECT (HEAT) COMBCHAMBER TO (ECONOMIZER, DRUMSYST::RISERS,  
SUPERH1, SUPERH2, SUPERH3, REHEATER)

CONNECT (STEAM) DRUMSYST::DRUM TO SUPERH1 TO ATTEMP1 →  
TO SUPERH2 TO ATTEMP2 TO SUPERH3 TO →  
CONTROLVALVE TO HPTURB TO REHEATER TO IPTURB →  
TO LPTURB TO CONDENSOR

·  
·  
·

END

model powerstation

submodel drumsyst  
submodel (superheater) superh1, superh2, superh3  
submodel (attemperator) attemp1, attemp2  
submodel reheater  
submodel controlvalve  
submodel (turbsection) HPTurb  
submodel IPTurb  
submodel LPTurb  
submodel condensor  
submodel (preheater) preh1, preh2, preh3, preh4, preh5,  
 preh6, preh7  
submodel splitsteam  
submodel dearator  
submodel feedwaterpump  
submodel feedwatervalve  
submodel combchamber  
submodel economizer

connect (heat) combchamber to (economizer,  
 drumsyst::risers, superh1, superh2, superh3, reheater)

connect (steam) drumsyst::drum to superh1 to attemp1 ->  
to superh2 to attemp2 to superh3 to ->  
 controlvalve to HPTurb to reheater to IPTurb ->  
to LPTurb to condensor

connect (extractsteam) HPTurb to preh7,  
 IPTurb to (preh6, preh5, preh4,  
 splitsteam to (dearator, preh3) ),  
 LPTurb to (preh2, preh1)

connect (feedwater) condensor to preh1 to preh2 to ->  
 preh3 to dearator to feedwaterpump to preh4 ->  
to preh5 to preh6 to preh7 to ->  
 feedwatervalve to ->  
 (economizer to drumsyst::drum, attemp1, attemp2)

connect (condensate) preh7 to preh6 to preh5 ->  
to preh4 to dearator,  
 preh3 to preh2 to preh1 to condensor

connect (power) HPTurb to IPTurb to LPTurb

HPTurb.N1 = 0  
 LPTurb::LP3.Wp = 0

end

MODEL TYPE SUPERHEATER

CUT INSTEAM (W, H1, P1)

CUT OUTSTEAM (W, H2, P2)

PATH STEAM < INSTEAM - OUTSTEAM >

CUT HEAT (Q)

PARAMETER Cm, m, K, Vs, F

LOCAL Tm, TmH, T2, T2H, R2

$$P1^{**2} - P2^{**2} = F * W^{**2}$$

{ ENERGY BALANCE }

{ DER(m\*Cm\*Tm + Vs\*R2\*H2) = }

$$(m * Cm * TmH + Vs * R2) * \underline{DER}(H2) = Q - W * (H2 - H1)$$

$$Tm = T2 + K * W * (H2 - H1)$$

$$TmH = T2H + K * W$$

$$R2 = RHP(H2, P2)$$

$$T2 = THP(H2, P2)$$

$$T2H = THPH(H2, P2)$$

END

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1. INTRODUCTION

2. MODELS AND MODELING

❧ 3. COMPUTER AIDED DESIGN

4. MORE COMPLICATED REGULATORS

5. CONCLUSIONS

## COMPUTER AIDED DESIGN

- PEOPLE WILL NOT USE THINGS THEY DO NOT FEEL COMFORTABLE WITH.
- ROLE OF EDUCATION ON MANY LEVELS.
- GOOD NUMERICS HAS LARGELY BEEN OVERLOOKED IN AUTOMATIC CONTROL. NONNUMERIC COMPUTER SCIENCE HAS BEEN EVEN MORE NEGLECTED.
- EVEN IF A GOOD SUBROUTINE LIBRARY IS AVAILABLE IT IS A SUBSTANTIAL EFFORT TO OBTAIN A WORKING DESIGN PROGRAM.
- C A D IS A CONVENIENT WAY TO PACKAGE THEORY. CORRECTLY DONE, IT IS EASY TO LEARN AND EASY TO USE.

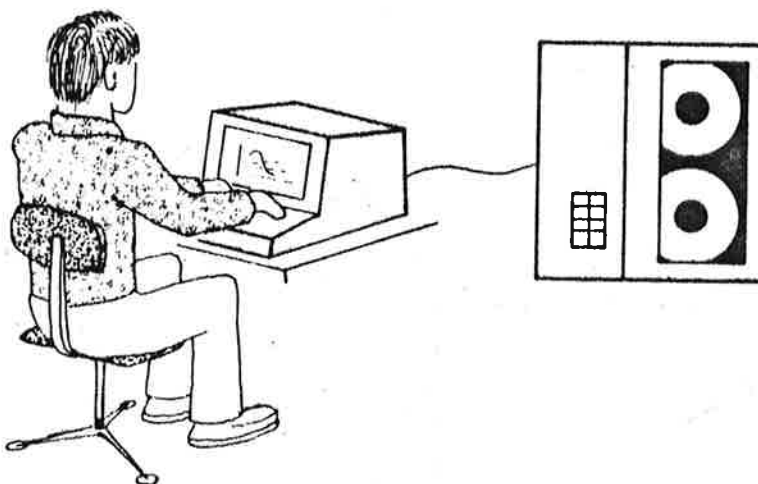
# COMPUTER AIDED ANALYSIS AND DESIGN

## BACKGROUND

MANY METHODS ARE CONCEPTUALLY SIMPLE  
BUT THEIR DETAILS MAY BE MESSY

## SOLUTION

COMBINE MAN'S INTUITION WITH THE COMPUTERS  
CALCULATING CAPACITY



## EXAMPLES

SIMNON

IDPAC

MODPAC

SYNPAC

## SYNPAC EXAMPLE

## SYSTEM FILE:

DYNAMICS

A,B,C,D

COVARIANCES

R1,R12,R2

LOSSFUNCTION

Q1,Q12,Q2

SAMPLING PERIOD H

$$DX/DT = Ax + Bu + v$$

$$Y = Cx + Du + E$$

$$R1 = \text{cov}(v)$$

$$R12 = \text{cov}(v, E)$$

$$R2 = \text{cov}(E)$$

$$J = \int_0^{\infty} [x^T Q1 x + 2x^T Q12 u + u^T Q2 u] dt$$

## MACRO DESIGN ALPHA

ALTER Q1 3 3 ALPHA

FOR H = 0.5 TO 5 STEP 0.5

SAMP DSYS ← CSYS

TRANS Q DSYS ← CSYS

TRANS R DSYS ← CSYS

OPTFB L ← DSYS

KALFI K ← DSYS

CONNECT CLSYS ← DSYS K L

SIMU Y X ← CLSYS UREF

PLOT X(1) X(7) X(8) XE(1) U

NEXT H

END {MACRO}

EDIT SYSTEM FILE

INPUT UREF ← STEP

DESIGN 3

DESIGN 8

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## TECHNOLOGY

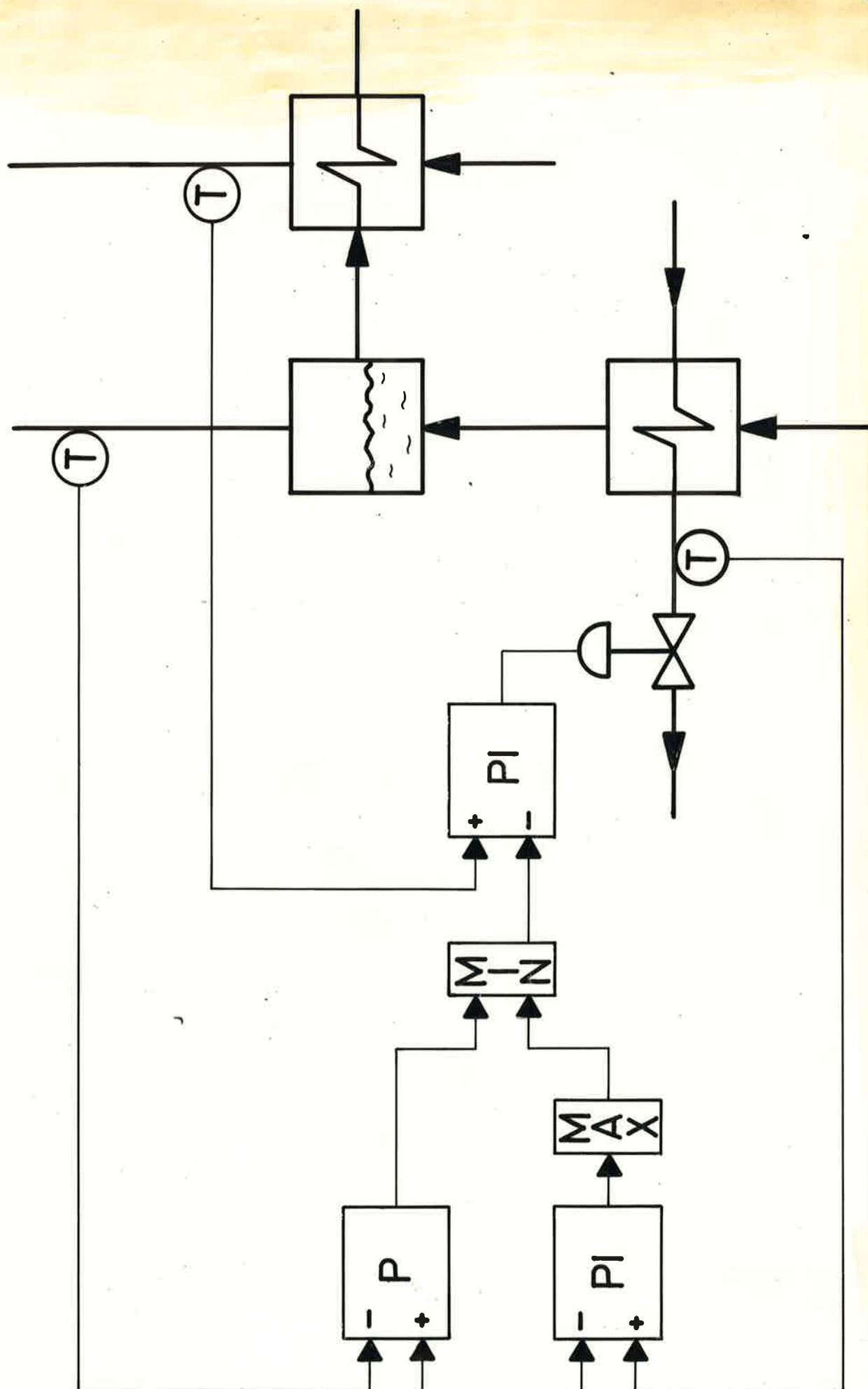
- TECHNOLOGY FOR MAKING MORE COMPLICATED REGULATORS IS ECONOMICALLY FEASIBLE (SINGLE LOOP  $\mu$ -P CONTROLLERS AVAILABLE ON MARKET).
- SIMPLE CONTROLLERS LIKE PID WORK WELL IN MANY CASES BUT THERE ARE SITUATIONS WHERE IT IS DEFINITELY WORTH-WHILE TO DO MORE.
- CHALLENGING PROBLEMS:
  - UNDERSTAND HOW THE NONLINEAR REGULATORS WORK
  - STABILITY, CONVERGENCE
  - USE INSIGHT TO MAKE IMPROVED ALGORITHMS
  - A RICH CHOICE OF DIFFERENT STRUCTURES
- EXAMPLES:

PROCESS CONTROL

AUTOMATIC / MANUAL, RESET WINDUP FEATURES

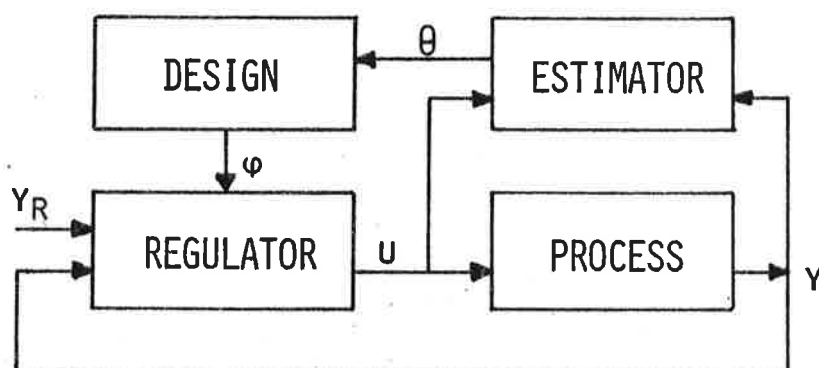
ADAPTIVE CONTROL

SPECIAL NONLINEAR STRUCTURES



## BASIC CONFIGURATION

### EXPLICIT ALGORITHM

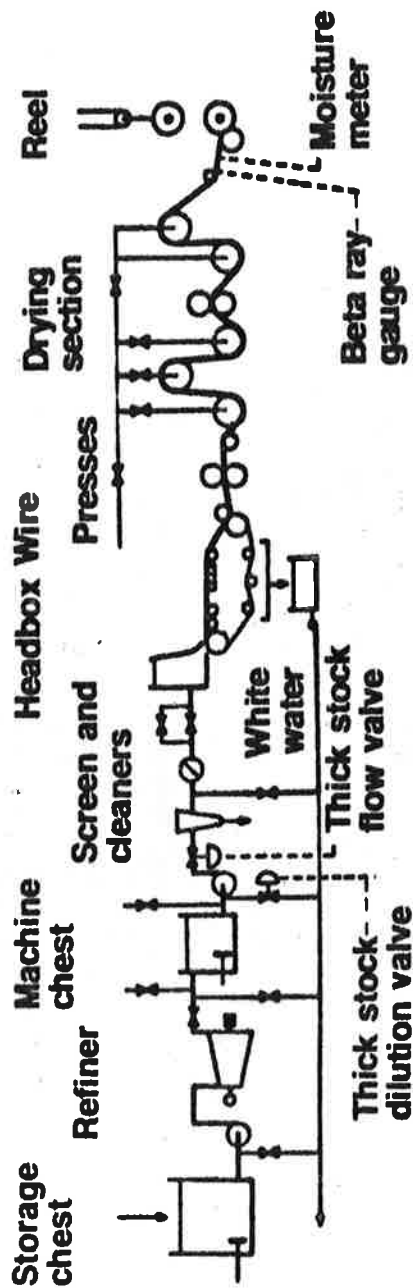


### TWO COMPONENTS

- PARAMETER ESTIMATOR
- CONTROLLER DESIGN

### RELATIONS TO DESIGN OF KNOWN SYSTEMS

# BASIS WEIGHT CONTROL OF PAPER MACHINE



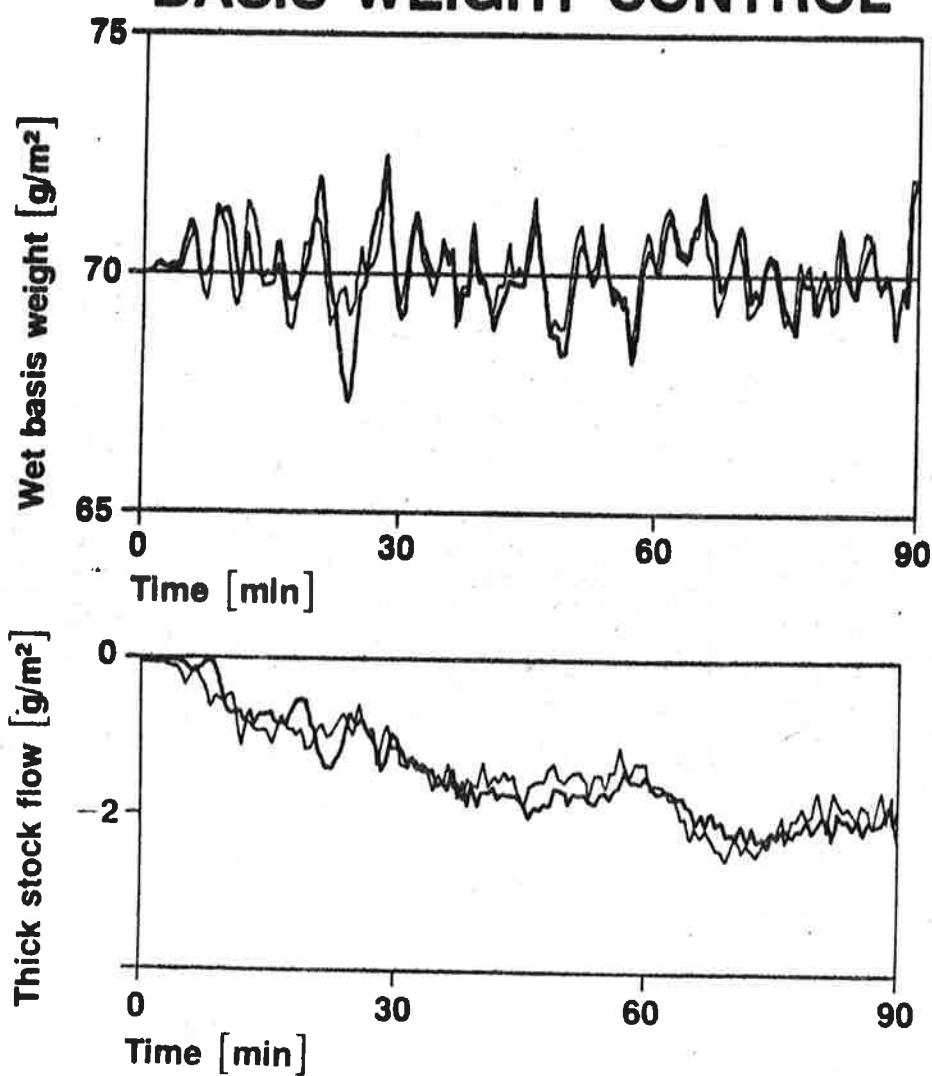
SECOND ORDER MODEL  
TWO TIME DELAYS  
SEVEN PARAMETERS

$$\Delta y(t) = \frac{4.61q - 4.05}{q^2 - 1.283q + 0.495} \Delta u(t-2) +$$

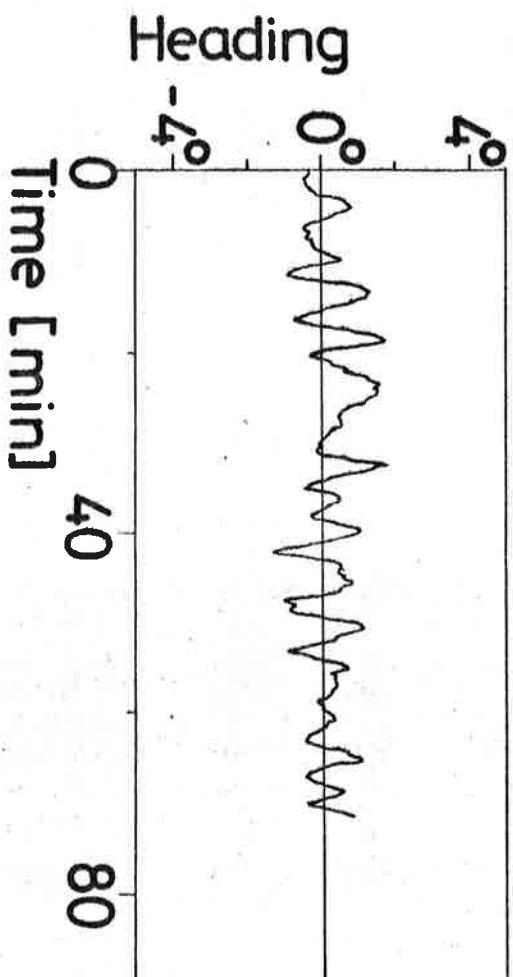
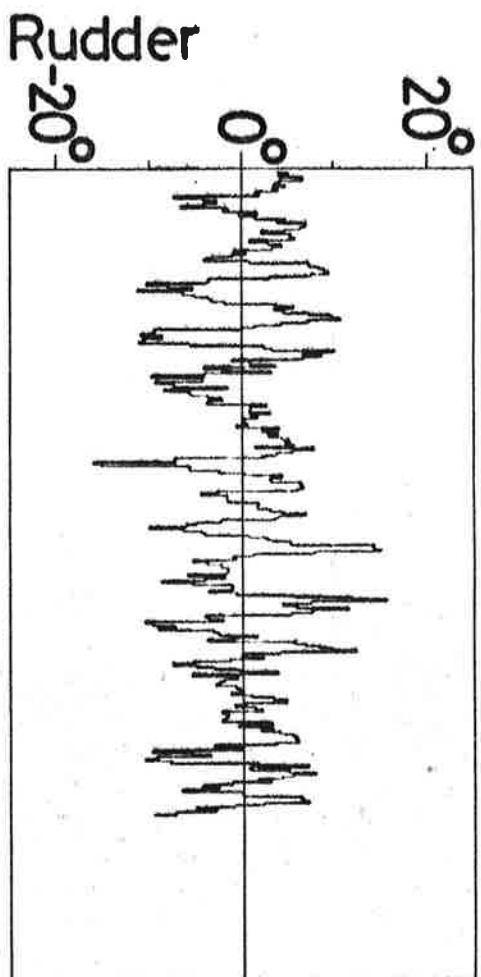
$$+ 0.382 \frac{q^2 - 1.438q + 0.550}{q^2 - 1.283q + 0.495} e(t)$$

REF K. J. Å. INTRODUCTION TO STOCHASTIC CONTROL THEORY

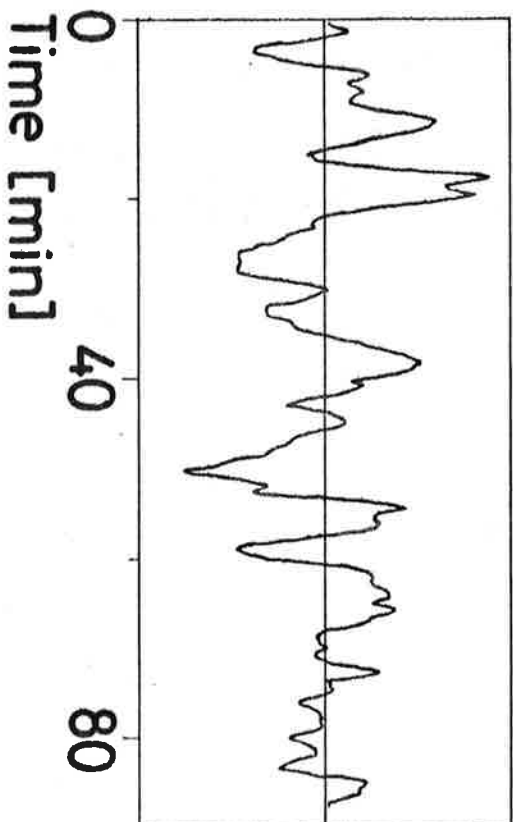
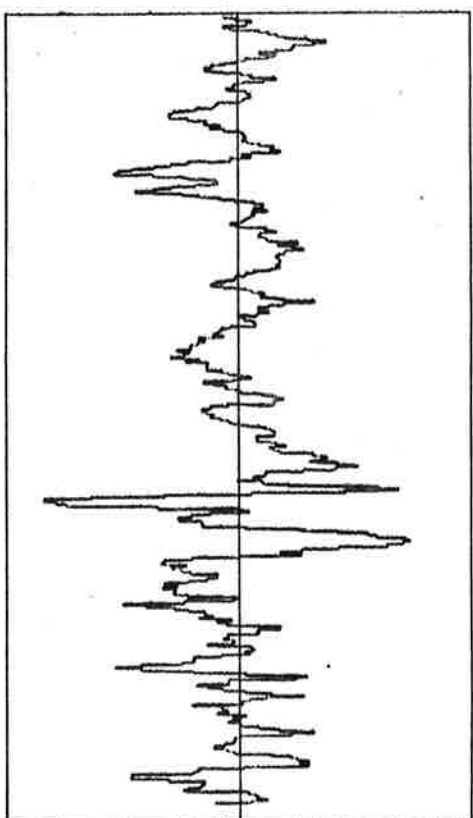
# COMPARISON OF ADAPTIVE (THICK LINE) BASIS WEIGHT CONTROL WITH OPTIMALLY TUNED (THIN LINE) BASIS WEIGHT CONTROL



Adaptive



PID



## CONCLUSIONS

### MODELING

MODELING IS OFTEN THE KEY TO GOOD APPLICATIONS.

SELECTION OF MODEL COMPLEXITY CRUCIAL FOR APPLICATION OF STATE SPACE METHODS.

NONNUMERIC COMPUTER SCIENCE OFFERS INTERESTING POSSIBILITIES FOR MODELING AND MANIPULATION OF LARGE SYSTEMS.

TO EXPLORE POSSIBLE USES OF NONNUMERIC COMPUTER SCIENCE IN AUTOMATIC CONTROL IS IN ITSELF A CHALLENGING PROBLEM.

### COMPUTER AIDED DESIGN

CAD IS IMPORTANT IN MAKING THEORY EASILY AVAILABLE IN COST EFFECTIVE WAY.

MUCH WORK REMAINS TO DESIGN RELIABLE NUMERICS FOR MANY ANALYSIS AND DESIGN PROCEDURES.

FEASIBILITY OF CAD HAS BEEN DEMONSTRATED. IT IS STILL A LONG WAY TO GO BEFORE THE TOOLS ARE REFINED AND WIDELY SPREAD.

### IMPLEMENTATION

NONLINEAR AND ADAPTIVE CONTROLLERS ARE FEASIBLE TO IMPLEMENT AND HARD TO RESIST. MANY CHALLENGING THEORETICAL PROBLEMS WILL BE GENERATED.