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REFLECTIONS ON THEORY AND PRACTICE OF AUTOMATIC CONTROL

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Reflections on theory and practice of automatic control.

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This 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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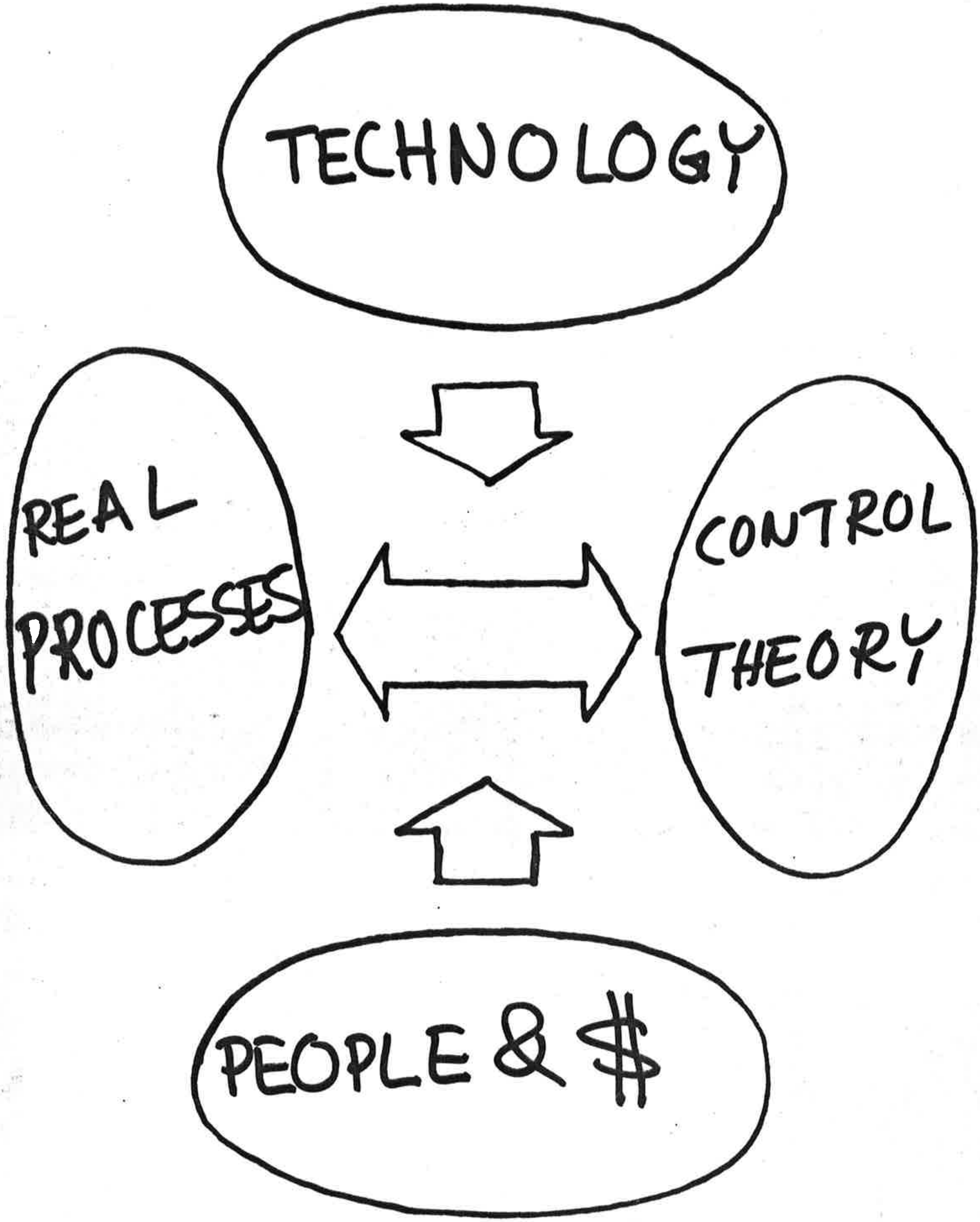
REFLECTIONS ON THEORY AND PRACTICE OF AUTOMATIC CONTROL

K. J. ÅSTRÖM

1. INTRODUCTION
   - BACKGROUND
   - HEDGING
2. MODELS AND MODELING
3. COMPUTER AIDED DESIGN
4. MORE COMPLICATED REGULATORS
5. CONCLUSIONS


TECHNOLOGY
REAL PROCESSES
CONTROL THEORY
PEOPLE & $

REFLECTIONS ON THEORY AND PRACTICE OF AUTOMATIC CONTROL

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

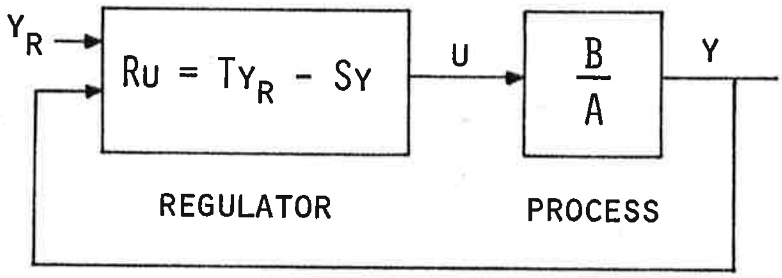
POLE-PLACEMENT DESIGN

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

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

REGULATOR STRUCTURE:

T/R FEEDFORWARD S/R FEEDBACK



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!

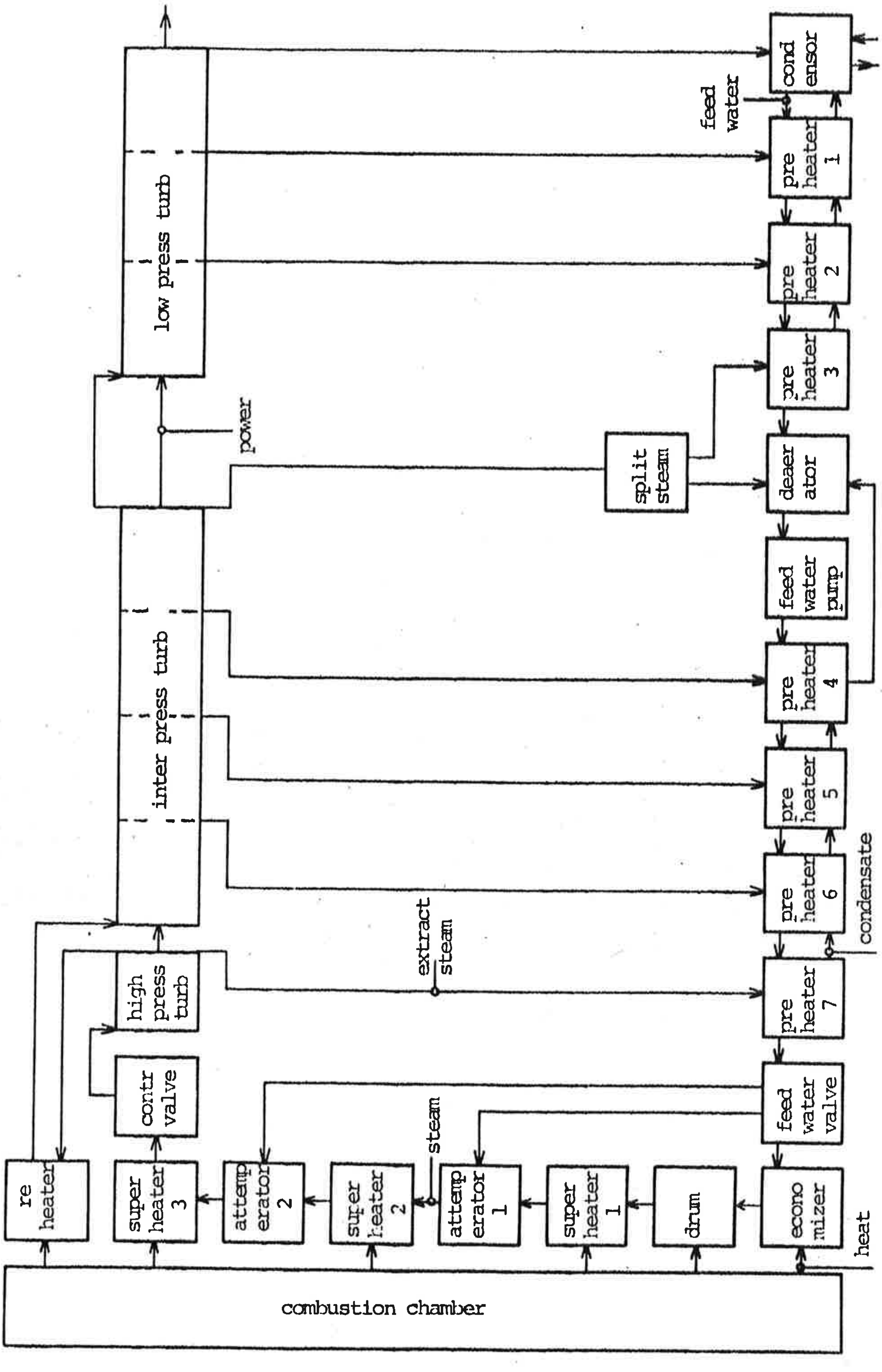

low press turb
inter press turb
high press turb
contr valve
power
cond ensor
feed water
pre heater 1
pre heater 2
pre heater 3
split steam
deaer ator
feed water pump
pre heater 4
pre heater 5
pre heater 6
condensate
extract steam
pre heater 7
feed water valve
re heater
super heater 3
attemp erator 2
super heater 2
steam
attemp erator 1
super heater 1
drum
econo mizer
heat
combustion chamber

Fig. 7.7

```
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 = Ø
LPturb::LP3.Wp = Ø

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)*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
```

REFLECTIONS ON THEORY AND PRACTICE OF AUTOMATIC CONTROL

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.

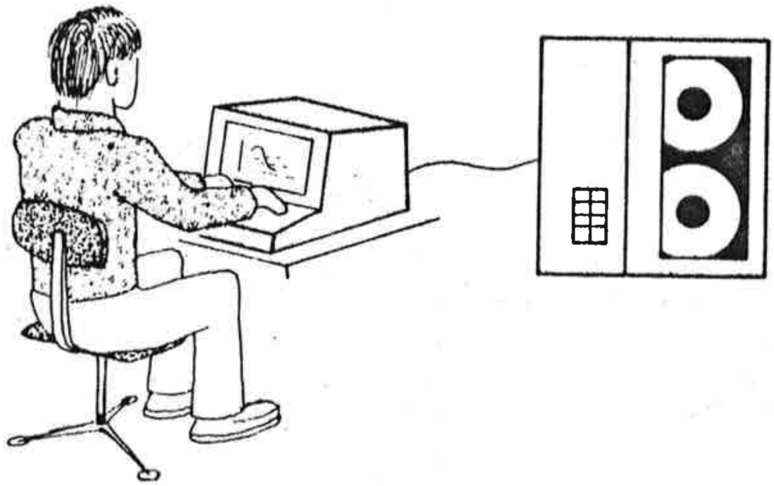
COMPUTER AIDED ANALYSIS AND DESIGN

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 — $DX/DT = Ax + Bu + v$

A,B,C,D — $Y = Cx + Du + e$

COVARIANCES

R1,R12,R2 — $R1 = cov(v)$, $R12 = cov(v,e)$, $R2 = cov(e)$

LOSSFUNCTION

Q1,Q12,Q2

SAMPLING PERIOD H

$$J = \int_0^\infty \left[x^T Q1 x + 2x^T Q12 u + u^T Q2 u\right] DT$$

```
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
```

REFLECTIONS ON THEORY AND PRACTICE OF AUTOMATIC CONTROL

1. INTRODUCTION

2. MODELS AND MODELING

3. COMPUTER AIDED DESIGN

4. MORE COMPLICATED REGULATORS

5. CONCLUSIONS

T E C H N O L O G Y

- TECHNOLOGY FOR MAKING MORE COMPLICATED REGULATORS IS ECONOMICALLY FEASIBLE (SINGLE LOOP μ-P CONTROLLERS AVAILABLE ON MARKET).

- SIMPLE CONTROLLERS LIKE P I D 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

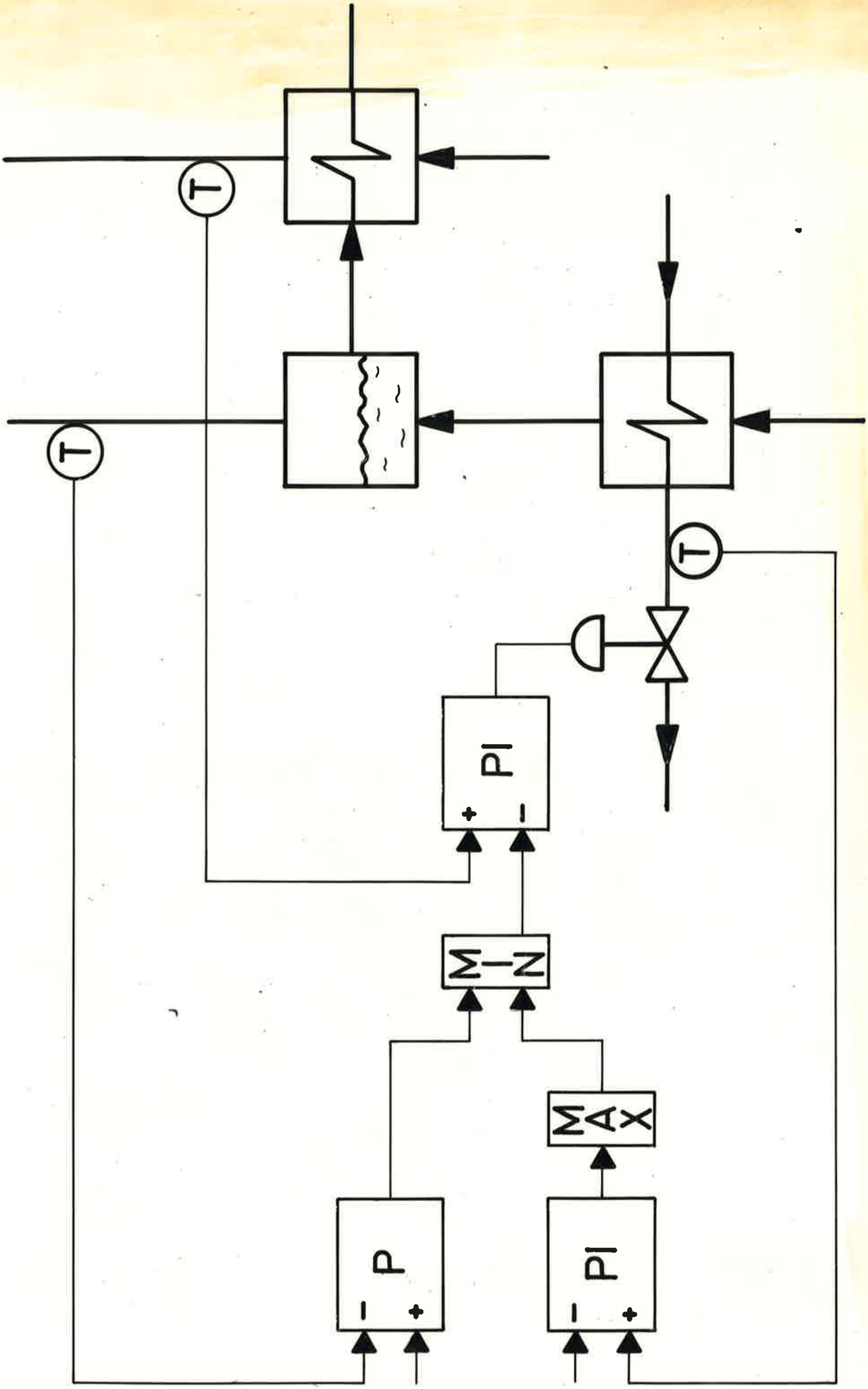
- EXAMPLES:

  PROCESS CONTROL

  AUTOMATIC / MANUAL, RESET WINDUP FEATURES

  ADAPTIVE CONTROL

  SPECIAL NONLINEAR STRUCTURES


T
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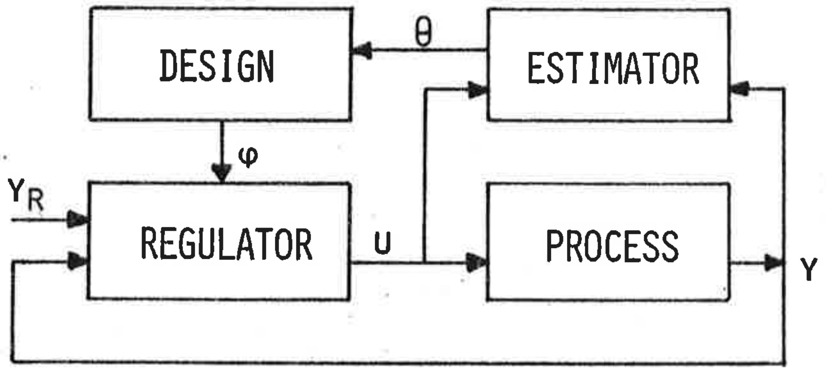
PI
MIN
MAX
P
PI

BASIC CONFIGURATION

EXPLICIT ALGORITHM

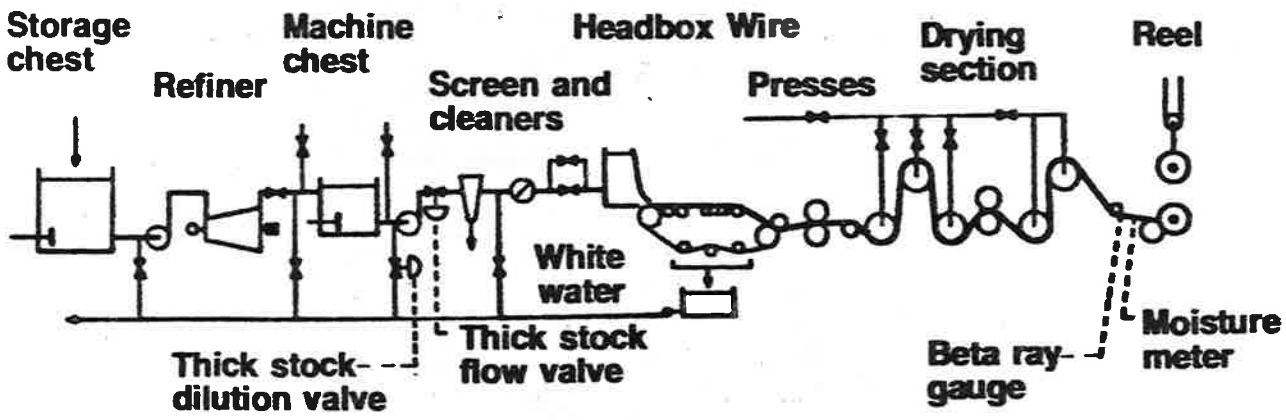


TWO COMPONENTS

- PARAMETER ESTIMATOR
- CONTROLLER DESIGN

RELATIONS TO DESIGN OF KNOWN SYSTEMS

BASIS WEIGHT CONTROL OF PAPER MACHINE



SECOND ORDER MODEL
TWO TIME DELAYS
SEVEN PARAMETERS

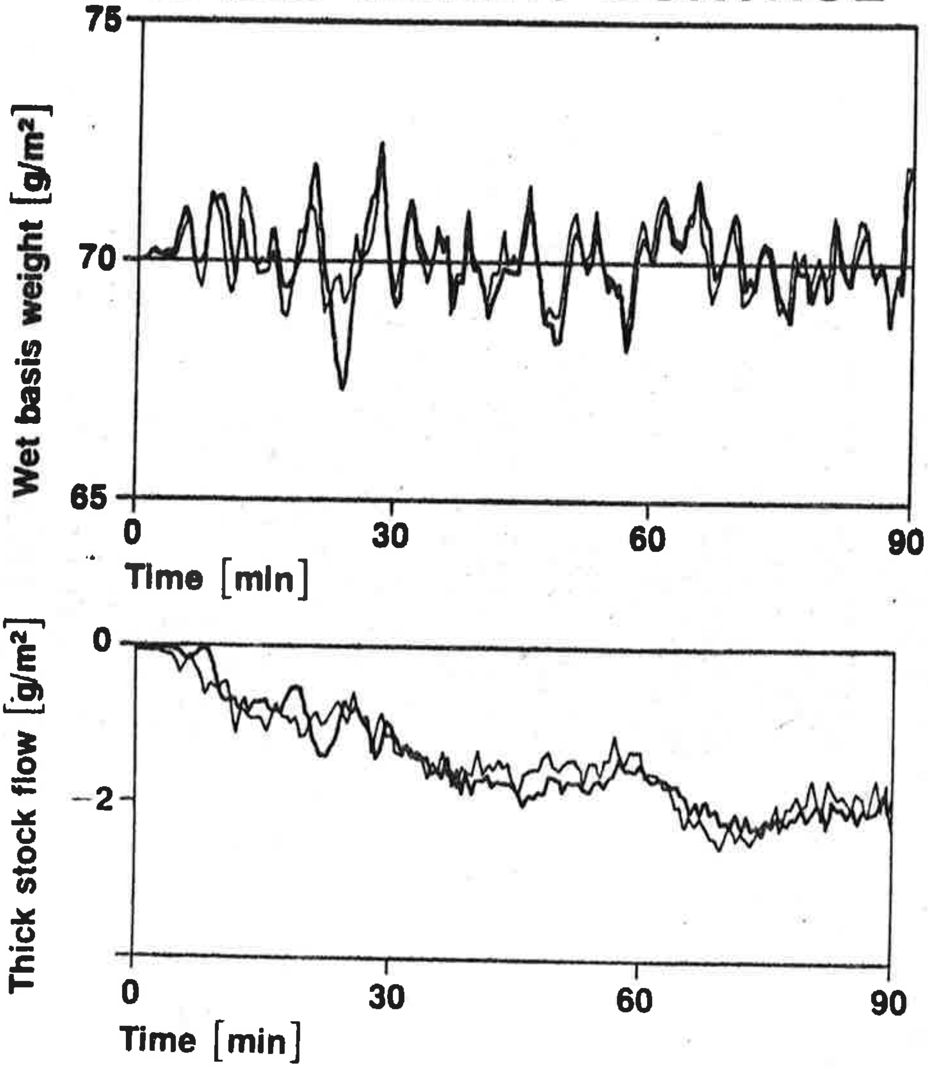
$$\Delta y(t) = \frac{4.61q - 4.05}{q^2 - 1.283q + 0.495} \Delta u(t-2) +$$

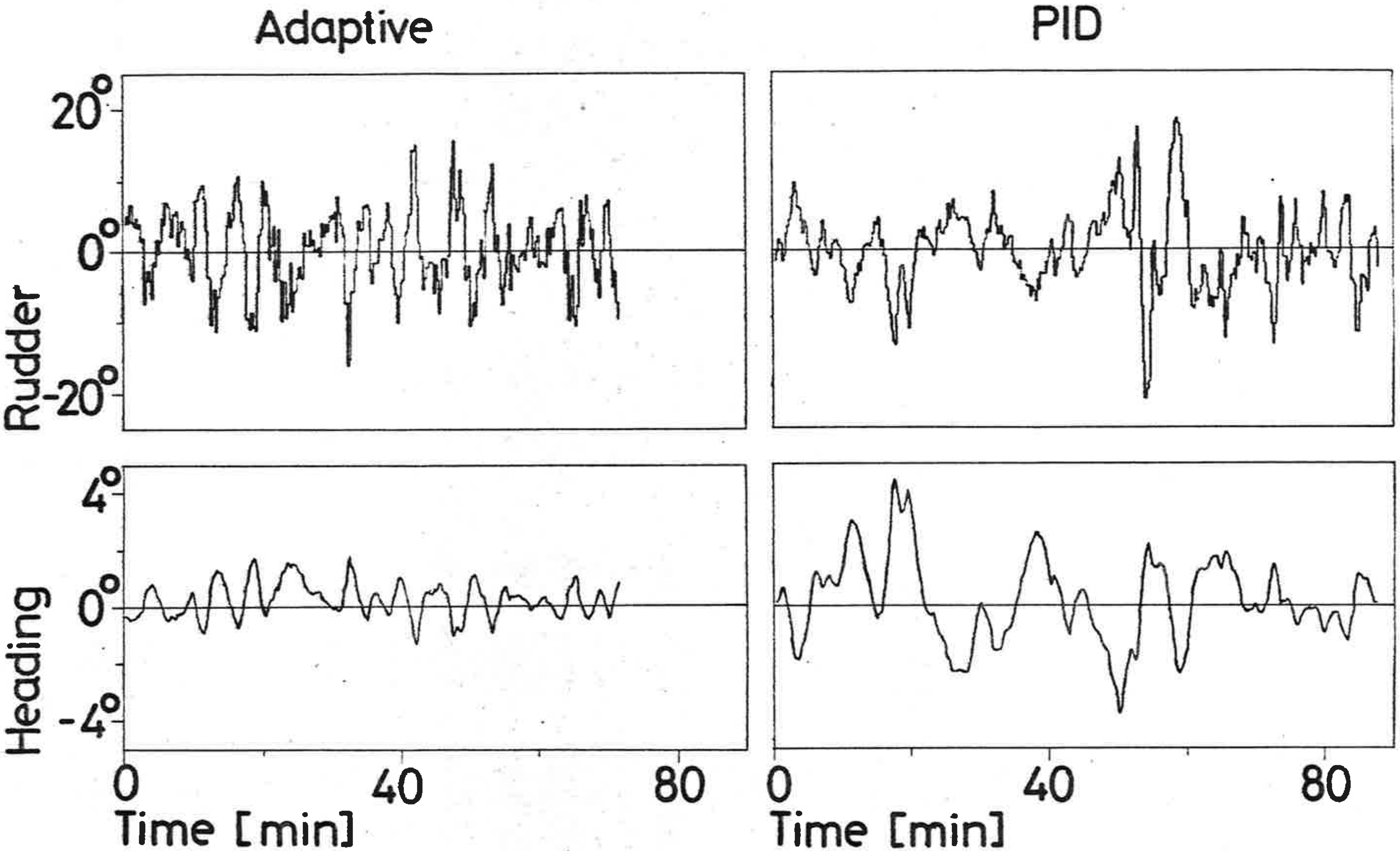
$$+ 0.382 \frac{q^2 - 1.438q + 0.550}{q^2 - 1.283q + 0.495} e(t)$$

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

ASTRÖM--18

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




Adaptive
PID
Rudder
20°
0°
-20°
Heading
4°
0°
-4°
0
40
80
Time [min]
0
40
80
Time [min]

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.