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CONSOLE: A CAD TANDEM FOR OPTIMIZATION-BASED DESIGN INTERACTING WITH USER-SUPPLIED SIMULATORS

By

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ABSTRACT

The most challenging task when designing a complex engineering system is that of coming up with an appropriate system "structure." This task calls extensively upon the engineer's ingenuity, creativity, intuition and experience. After a structure has been (maybe temporarily) selected, it remains to determine the "best" value of a number of "design parameters." The engineer's input is still essential here, as multiple tradeoffs are bound to appear. However, except in the simplest cases, achieving anything close to optimal would be impossible without the support of numerical optimization. Providing such support while emphasizing tradeoff exploration through man-machine interaction is the purpose of interactive optimization-based design packages such as CONSOLE (Proceedings of American Control Conference 1988). A requirement for CONSOLE is that the parameters to be optimally adjusted vary over a continuous (as opposed to discrete) set of values.

CONSOLE employs a recently developed design methodology (International Journal of Control 43:1693-1721) which provides the designer with a congenial environment to express his problem as a multiple objective constrained optimization problem and allows him to refine his characterization of optimality when a suboptimal design is approached. To this end, in CONSOLE, the designer formulates the design problem using a high-level language and performs design task and explores tradeoff through a few short and clearly defined commands.

The range of problems that can be solved efficiently using a CAD tools depends very much on the ability of this tool to be interfaced with user-supplied simulators. For instance, when designing a control system one makes use of the characteristics of the plant, and therefore, a model of the plant under study has to be made available to the CAD tool. CONSOLE allows for an easy interfacing of almost any simulator the user has available.

To date CONSOLE has already been used successfully in many applications, including the design of controllers for a flexible arm and for a robotic manipulator and the solution of a parameter selection problem for a neural network (all under P. S. Krishnaprasad at the University of Maryland at College Park), the design of an RC controller for a radar antenna (under F. Emad at the University of Maryland at College Park), and the design of power filters (at the Westinghouse Defense and Electronics Center). In the case of the neural network application, CONSOLE was coupled to the nonlinear system simulator SIMNON.

CONSOLE :

A CAD Tandem for Optimization-Based Design Interacting with User-Supplied Simulators

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HISTORY

DELIGHT (Nye, Polak, Sangiovanni-Vincentelli, Tits) 1980 -
general purpose interactive package
+ optimization algorithms

DELIGHT.MaryLin (Fan, Nye, Tits) 1985 -
interactive optimization-based design package
for linear time-invariant systems

CONSOLE (Fan, Wang, Koninckx, Tits) 1987 -
interactive optimization-based design package
for engineering systems (with user-supplied
simulators)

CONSOLE

PARAMETRIC OPTIMIZATION IN DESIGN

Assume *structure* already chosen

Examples :

Circuit → Topology

Control System → Controller Structure

Earthquake Proof Building → Number and Position of Beams

Remain to choose *best* value of finitely many parameters

Examples :

Circuit → R, C, W, A, ...

Control System → Controller Gains, LQR/LQG Weighting Matrices, Q-parameterization, ...

Earthquake Proof Building → Beam Thickness, Amount of Steel, ...

CONSOLE

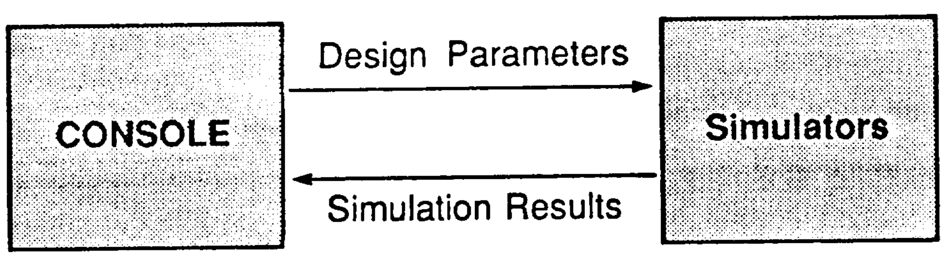
COMPONENTS FOR PARAMETERIC OPTIMIZATION

1. Design Methodology (Nye, Tits)

   Problem Formulation
   Optimal in what Sense ?
   Optimization Algorithm
   User-Machine Interaction

   → CONSOLE

2. Model and Simulation Tool → Simulators



CONSOLE

PROBLEM FORMULATION

Types of Specifications

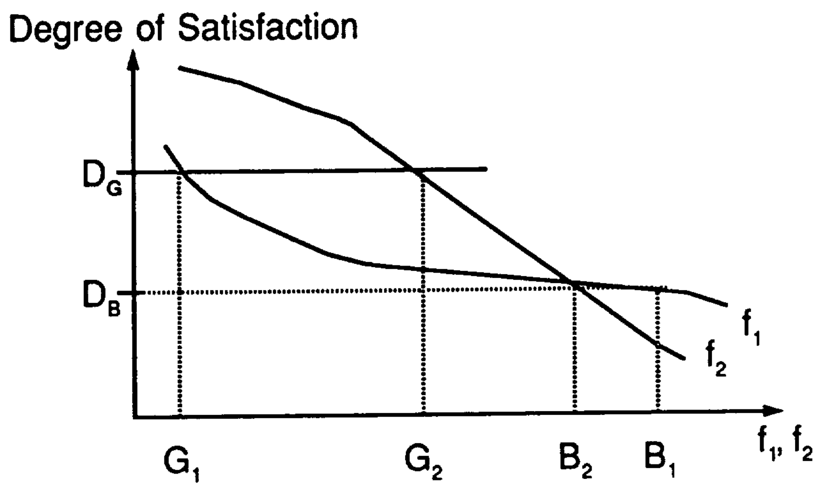
Objectives - The smaller (larger) the better.

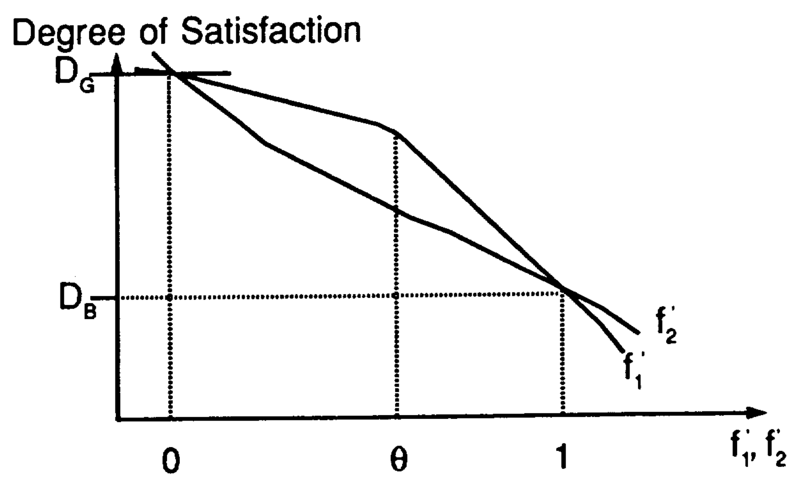
Soft Constraints - Aim for a *target* value. If unachievable, the smaller (larger) the better.

Hard Constraints - Specified value *must* be achieved.

CONSOLE

OPTIMAL IN WHAT SENSE ?





$$f'_i = \frac{f_i - G_i}{B_i - G_i} \qquad \min_x \max_i f'_i(x)$$

OPTIMIZATION ALGORITHM

Three Phase Feasible Direction Algorithm

Phase 1 (until all hard constraints are satisfied)

attempt to satisfy hard constraints (HC)

minimax on HC

Phase 2 (until all good values are achieved)

improve objectives (O) and soft constraints (SC)

minimax on O and SC

subject to satisfying HC

Phase 3

improve objectives

minimax on O

subject to satisfying HC and SC

CONSOLE

$$\min_{x} \max_{i} f_i(x)$$

subject to

$$g_k(x) \leqslant 0, \quad \forall k$$

where

$$f_i(x) = \max_{\omega} \varphi_i(x,\omega)$$

$$g_k(x) = \max_{\omega} \psi_k(x,\omega)$$

CONSOLE

USER-MACHINE INTERACTION

Purpose

Progressively refine problem definition

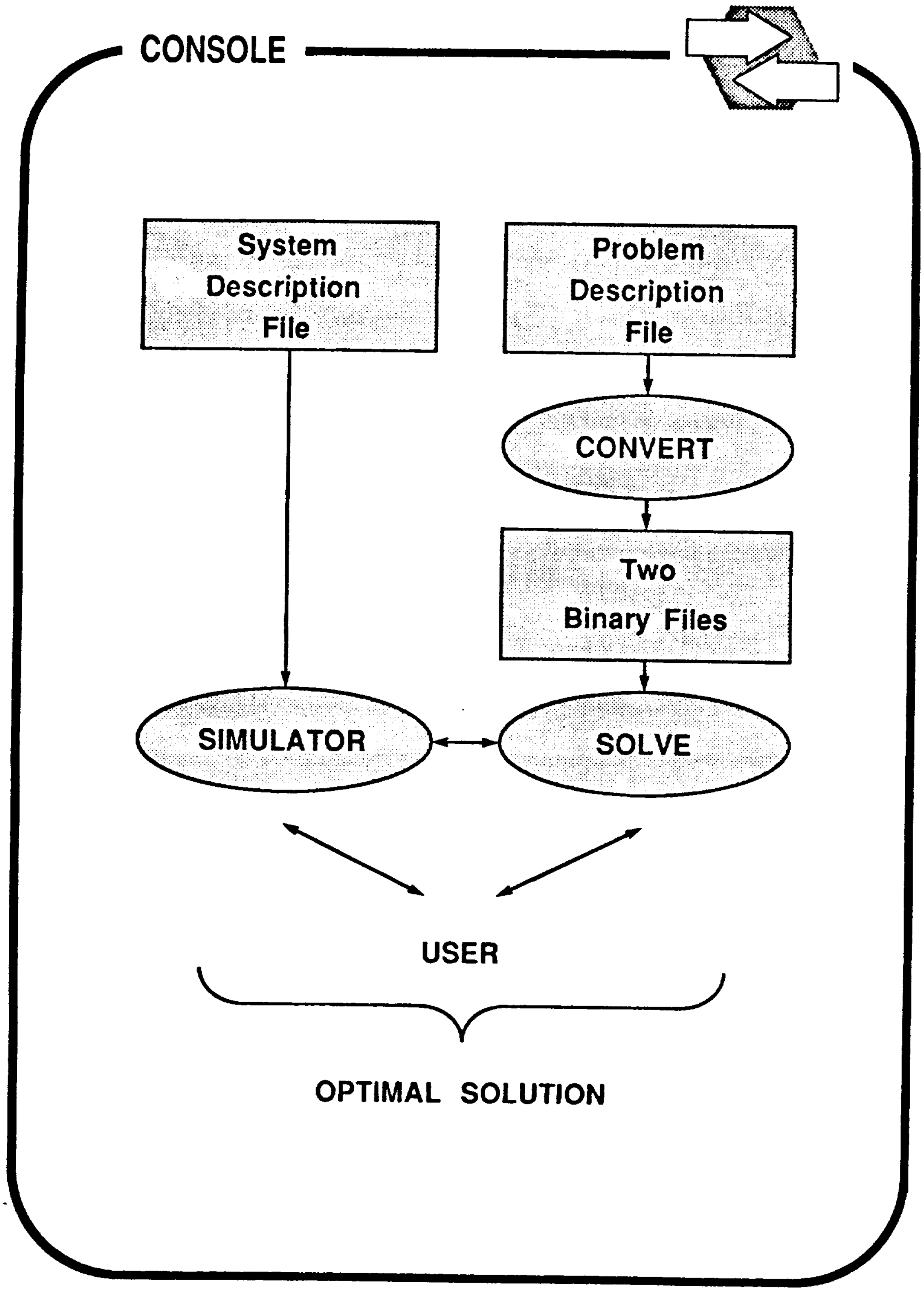
Means

- Information on status of design conveyed graphically to user (Pcomb, Ecomb).
- User steers design to *his* optimal solution by adjusting good/bad values/curves.

C 2

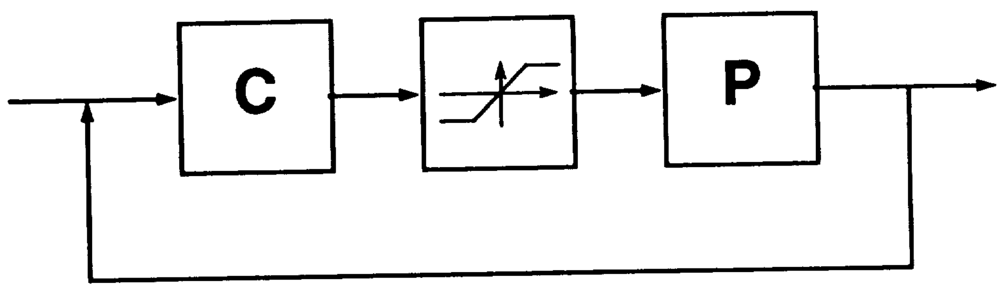
CONSOLE =

CONvert + SOLvE


CONSOLE
System Description File
Problem Description File
CONVERT
Two Binary Files
SIMULATOR
SOLVE
USER
OPTIMAL SOLUTION

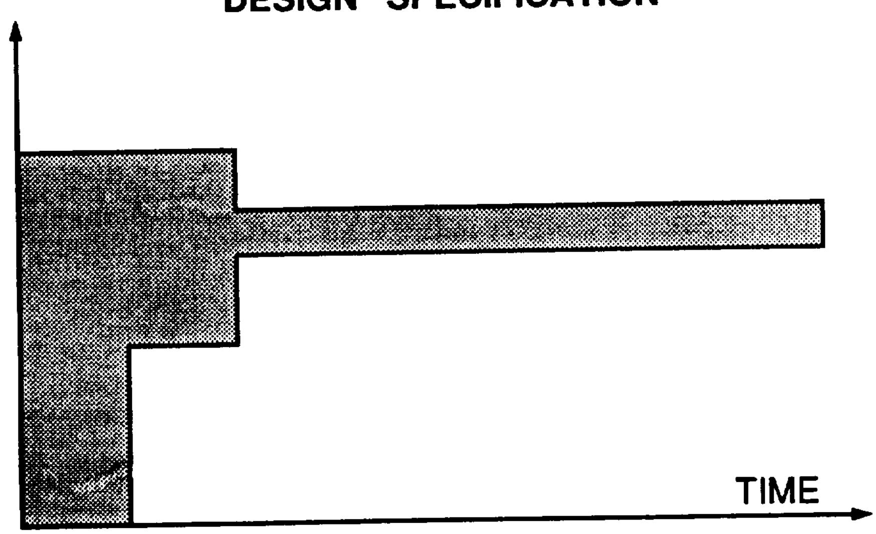
A SIMPLE DESIGN EXAMPLE

CONTROL SYSTEM



$$C(s) = K_p + \frac{K_I}{s} \qquad P(s) = \frac{s+1}{s^2}$$

DESIGN SPECIFICATION



CONSOLE

SYSTEM DESCRIPTION FILE FOR THE EXAMPLE (SIMNON*)

```
CONTINUOUS SYSTEM servo
STATE x1 x2 x3
DER dx1 dx2 dx3
x1:0
x2:0
x3:0
dx1 = x2
dx2 = if (e > 0.4) then 0.4
      else if (e < -0.4) then -0.4
      else e
dx3 = r - y
e = (r - y)*Kp + x3*Ki
y = x1+x2
r:1
Kp:0
Ki:0
END
```

*SIMNON was developed at the Lund Institute of Technology, Lund, Sweden

CONSOLE

PROBLEM DESCRIPTION FILE FOR THE EXAMPLE

```
design_parameter Kp init=1 variation=5
design_parameter Ki

functional_objective  "overshoot"
  for t from 0 to 20 by 0.1
  minimize  {
    double simnon_time_response();
    return simnon_time_response(Kp,Ki,"y",t);
    }
  good_curve={
    if (t <= 4)  return 1.05;
    else         return 1.01;
    }
  bad_curve ={
    if (t <= 4)  return 1.1;
    else         return 1.02;
    }

functional_objective  "settling time"
  for t from 2 to 20 by .1
  maximize  {
    ...
```

MAIN FEATURES OF CONSOLE

Problem formulation is closely related to the character of a design problem.

Problem formulation syntax is strict, but easy to use.

Efficient iteration between **CONVERT** and user for debugging the PDF.

SOLVE is interactive, with short and clearly defined commands providing efficient communication between the program and the user.

Interactive graphics provide the user with easy-to-interpret information on the current design (Pcomb, Ecomb).

User-supplied simulators can easily be linked with **SOLVE**.

CONSOLE

GLANCE AT APPLICATIONS

Design of a copolymerization reactor controller
(Butala, Choi, Fan)

Design of controllers for a flexible arm
(Wang, Krishnaprasad)

Design of a controller for a robotic manipulator
(Chen, Krishnaprasad)

H-infinity Design of ~~a~~ Sampled-Data Control Systems
(Yang, Levine)

Solution of a parameter selection problem
for a neural network
(Pati, Krishnaprasad *et al.*)

Design of an RC controller for a radar antenna
(Emad)

Design of power filters
(Glover, Walrath at Westinghouse Defense
and Electronics Center)

... and soon

Design of earthquake proof buildings
(Austin)

Design of controllers for X29 aircraft
(Reilly, Levine)

Design of circuits
(Westinghouse)

DESIGN OF A COPOLYMERIZATION REACTOR CONTROLLER

(**CONSOLE** + Copoly) (Butala, Choi, Fan)

Objectives and Constraints

- Molecular Weight
- Composition
- Final Volume
- Temperature
- Feed Flowrate

Manipulated Variables

$$\text{Temperature} = a_1 + a_2 t + a_3 t^2 + a_4 t^3$$
$$\text{Feed Flowrate} = b_1 + b_2 t + b_3 t^2 + b_4 t^3$$

Design Parameters = a_i's and b_i's

Results

```
Pcomb (Iter=  22) (Phase 2) (MAX_COST_SOFT= 0.0766327)

SPECIFICATION      PRESENT   GOOD                 G          B           BAD
FO1  (MN-MNs)^2    1.92e+06  0.00e+00 ************           |           2.50e+07
FO2  (CC-CCs)^2    3.88e-03  0.00e+00 ************           |           5.06e-02
C1   final vol     3.47e+00  4.00e+00 <--         |          |           4.10e+00
FC1  upper temp    3.53e+02  3.63e+02 <--         |          |           3.64e+02
FC2  lower temp    3.45e+02  3.28e+02 <--------------------------------- 3.23e+02
FC3  upper flow    9.70e-03  7.00e-02 <--         |          |           7.50e-02
FC4  lower flow    6.00e-03  0.00e+00 <--------------------------------- -5.00e-03
```

CONSOLE

DESIGN OF A DC DIRECT DRIVE MOTOR

(CONSOLE + Simnon) (Wang, Krishnaprasad)

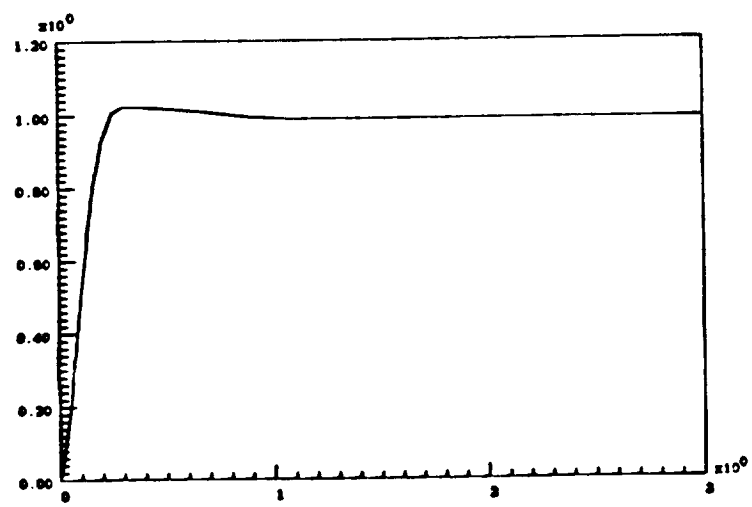
Objective

Position Profile

Design Parameters

Feedback Gains

Results



FUTURE ENHANCEMENTS

User Interface

More Powerful Optimization Algorithms

Gradient Computation