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SIMULATION FOR ENGINEERING

Using Chip Simulation to Optimize Engine Control

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Outline of the talk

Using Chip Simulation to Optimize Engine Control

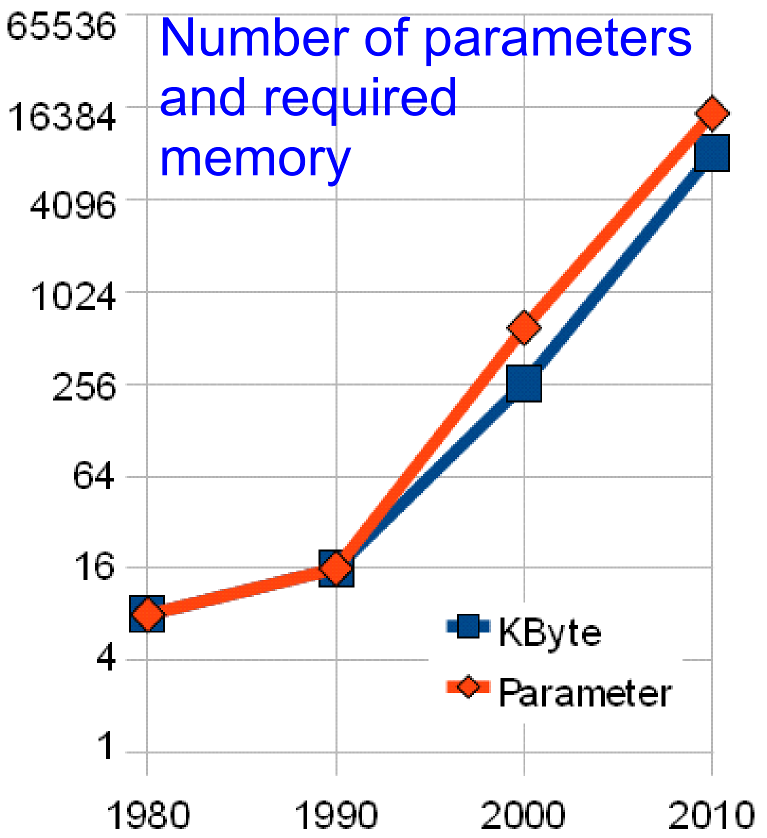
1. Motivation
2. Running ECU functions on PC via chip simulation
3. Coupling with least-squares optimization
4. Conclusion

Motivation

- number of engine control parameters doubles every few years
- budget for engine calibration does not

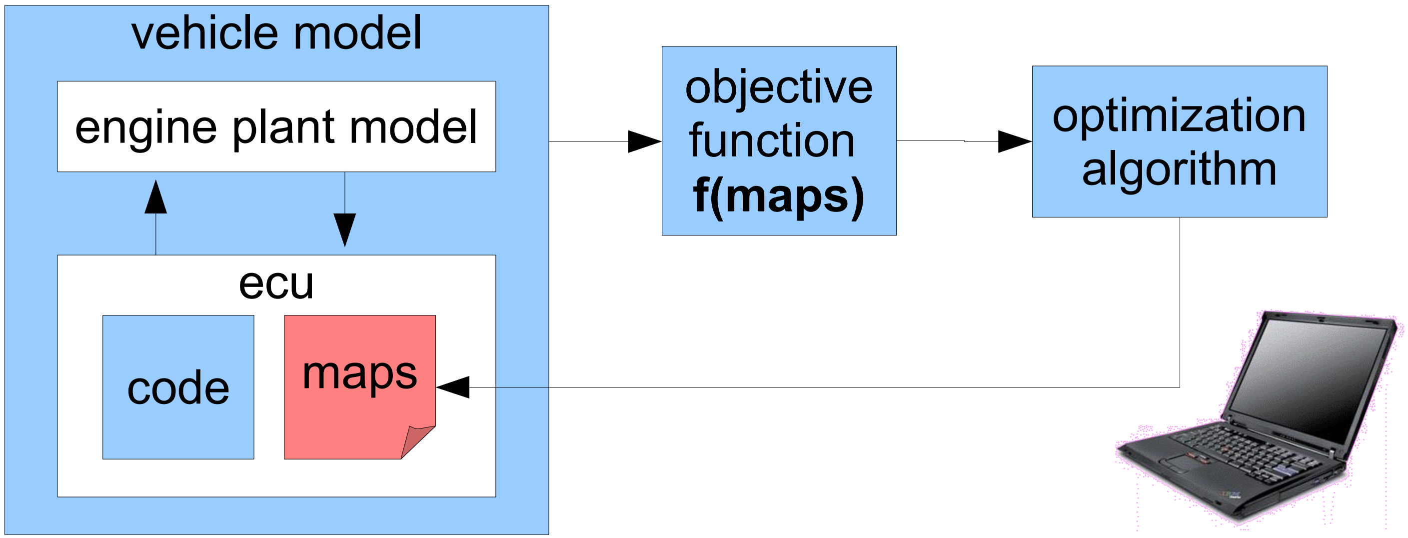
Idea

- increase degree of automation
- move calibration tasks from test rigs to PC and apply mathematical optimization



source: presentation of S. Ullmann (BMW) 5th Conference on DOE, 2009

Motivation: Model-based engine calibration



ECU source (C, Ascet, or Simulink model) typically not available for OEM

Challenge: how to simulate the ECU on PC?

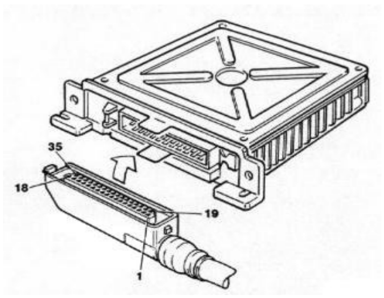
Options:

- **reverse engineer** the ECU function of interest, e. g. with Simulink
  → time consuming, error prone
- **simulate the hex** file of the ECU
  → less work, no modeling error

Simulating a hex file

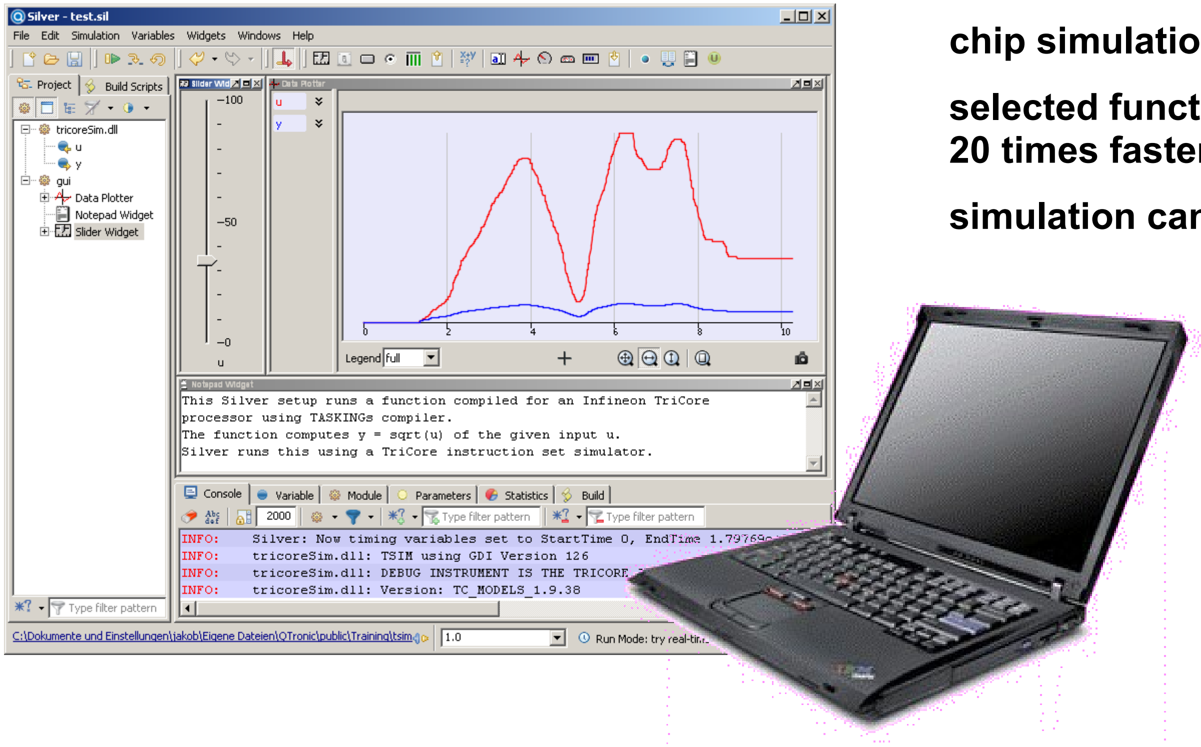
```
:020000040000FA
:0200000480007A
:200000003000000004FD00000000028000FD0080080200801C0200800507AFAFAFAFAFAF62
:20002000AFAFAFAFAFAFAFAFAFAFAFAF02000000D35A4822300402000000080FFFC0080C2
:20004000FECADEFAFEAFFECA0000000074FC00800010000310412007800008003020080C7
:20006000FECADEFAFEAFFECA0000000000000000010000779781BD000000000000000000F
:20008000000000000000000000000000000000000000000000000000000000000000000060
:2000A000000000000000000000000000000000000000000000000000000000000000000040
           00000000000000000000000000000000000000000000000000000000000000020
           0000000000000000000000000000000000000000000000000000000000000000
```

.hex



4 MB

Silver Chip Simulator
for TriCore chip family



chip simulation runs on PC with about 40 MIPS

**selected function run e.g.
20 times faster than realtime**

simulation can be exported as SFunction

TriCore Simulation in Silver 2.5

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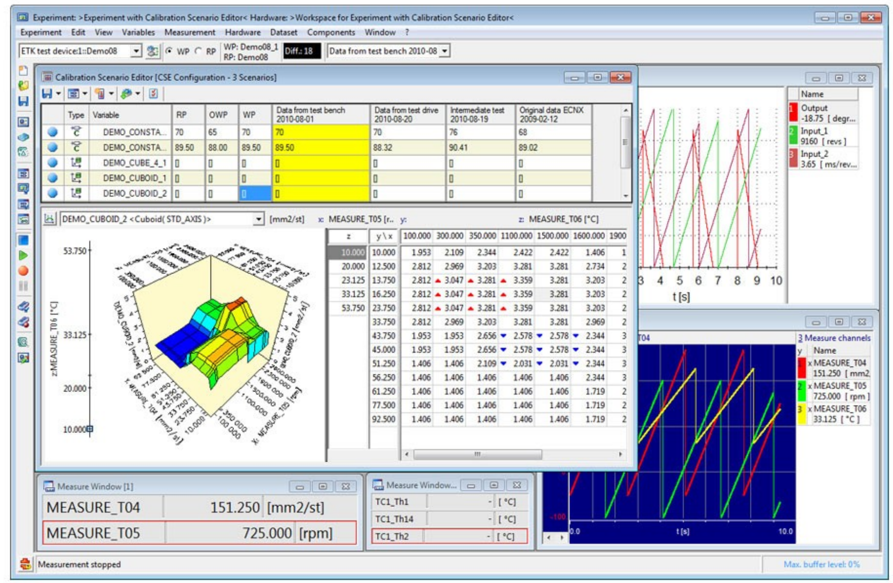
INCA or CANape for on-line calibration:
measure and tune running simulation



virtual ECU

ECU functions

RTOS emulation

4GB virtual memory

A2L conversion

XCP

TriCore emulation
40 MIPS

TCP/IP

vehicle simulation or measurements

Silver

SIMULINK Enabled
MathWorks Partner

Setting up a TriCore simulation

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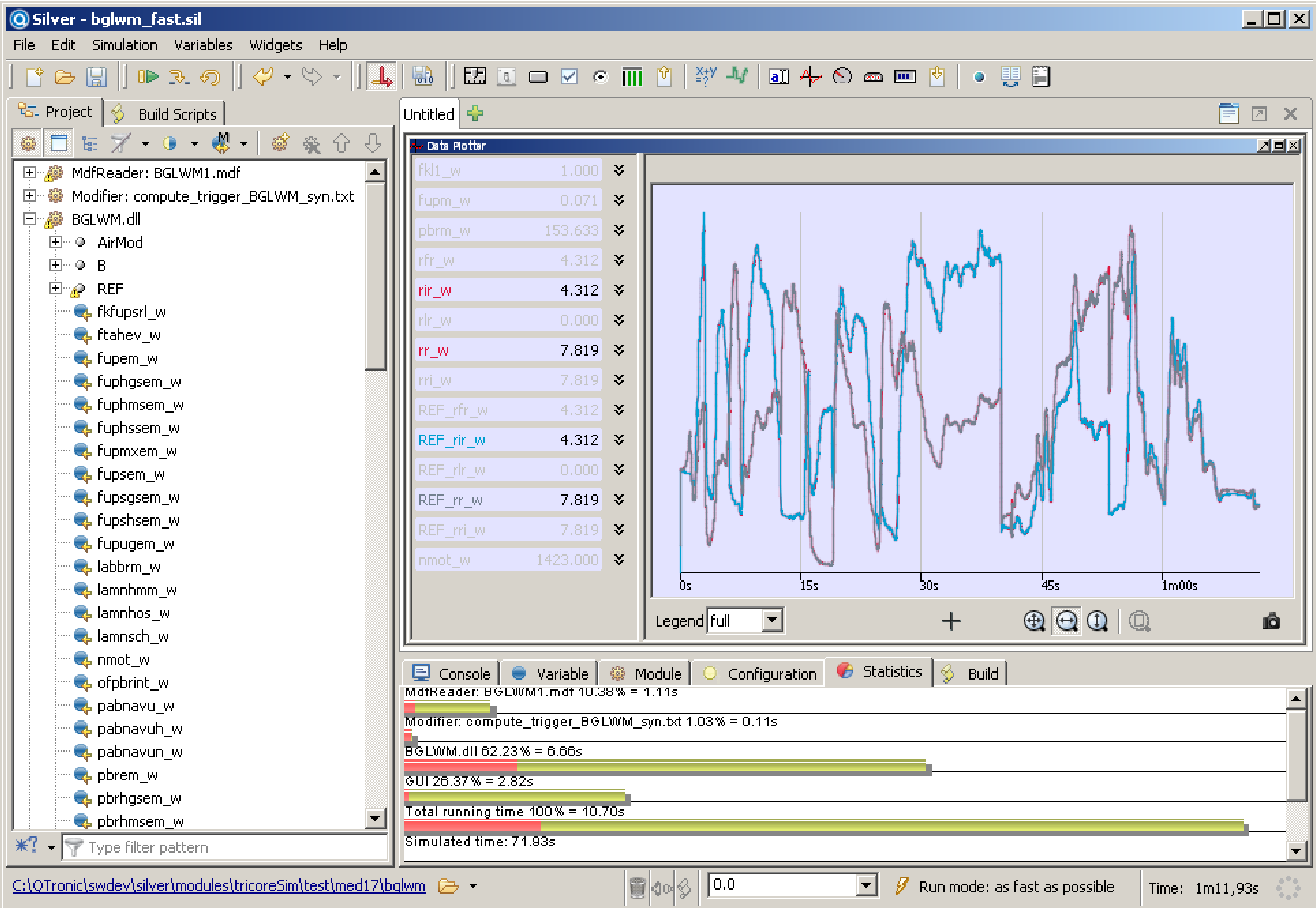
1. write spec.txt to specify what functions to run
2. step and debug the simulation in Silver debug mode
3. generate fast running SFunction or Silver module: runs without a2l and hex

```
# specification of sfunction or Silver module
hex_file(m12345.hex, TriCore_1.3.1)
a2l_file(m12345.a2l)
map_file(m12345.map)       # a TASKING or GNU map file
frame_file(frame.s)        # assembler code to emulate RTOS
frame_set(STEP_SIZE, 10)  # Silver step size in ms
frame_set(TEXT_START, 0xa0000000) # location of frame code

# functions to be simulated, in order of execution
task_initial(ABCDE_ini, 0)
task_initial(ABCDE_inisyn, 0)
task_triggered(ABCDE_syn, trigger_ABCDE_syn)
task_periodic(ABCDE_20ms, 20, 0)
task_periodic(ABCDE_200ms, 200, 0)

# interface of the generated sfunction or Silver module
a2l_function_inputs(ABCDE)
a2l_function_outputs(ABCDE)
a2l_function_parameters_defined(ABCDE)
```

Virtual ECU running in Silver: MED17



generated SFunction in MATLAB/Simulink

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spec.txt

.hex .map

.a2l frame.s

tcbuild

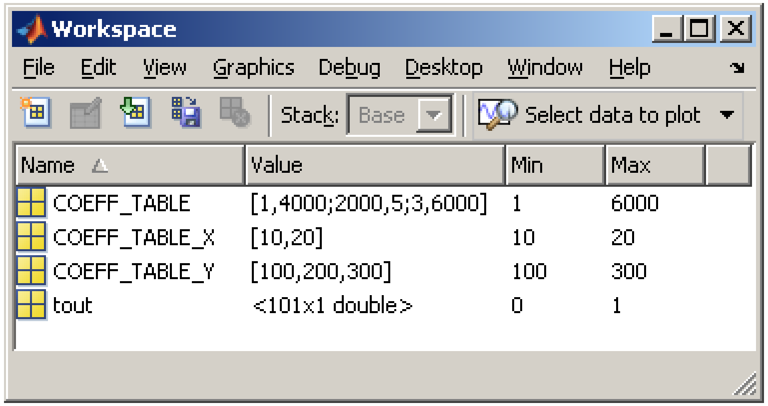
.mexw32

MATLAB/Simulink
S-function
40 MIPS

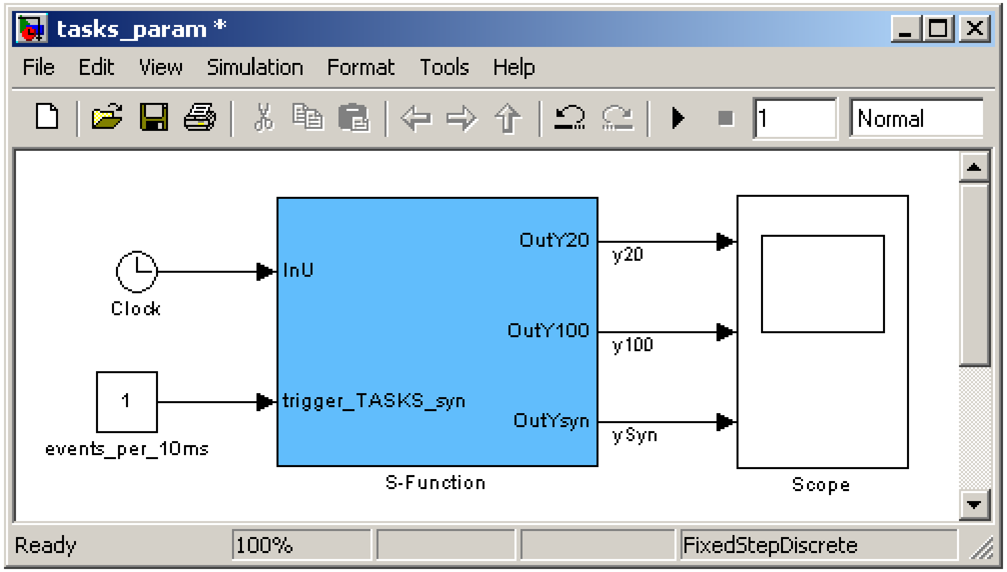
.mask.txt

default values for characteristics from HEX file as m script,

mask for S-function block and similar Simulink snippets



characteristics turned into MATLAB workspace variables
- read by S-function
- may be modified by script



Performance and Limitations

Run complex function for a measured scenario, 3.5 minutes

target	execution time	MIPS
Silver in debug mode	919.15 sec	0.41
generated Silver module or MATLAB/Simulink SFunction	9.30 sec	40.80
MED17 with TC1797, 180 Mhz	210.00 sec	270

Limitations
- instruction accurate, but not cycle accurate
- based on TriCore specification: 'silicon bugs' are not simulated
- PCP, CAN controllers and other on chip devices not modeled

Advantages
- no real-time requirement: simulate faster or slower than real-time
- 4 GB virtual memory available in virtual ECU
- zero-execution time model: simulated task runs infinitely fast
  hence: deterministic simulation without interrupts: easy to analyze

Optimization problem

Engine controller contains steady-state model of the engine

Objective

Tune parameters of the engine model
such that it fits given measurements

Least-squares optimization

Minimize goal function

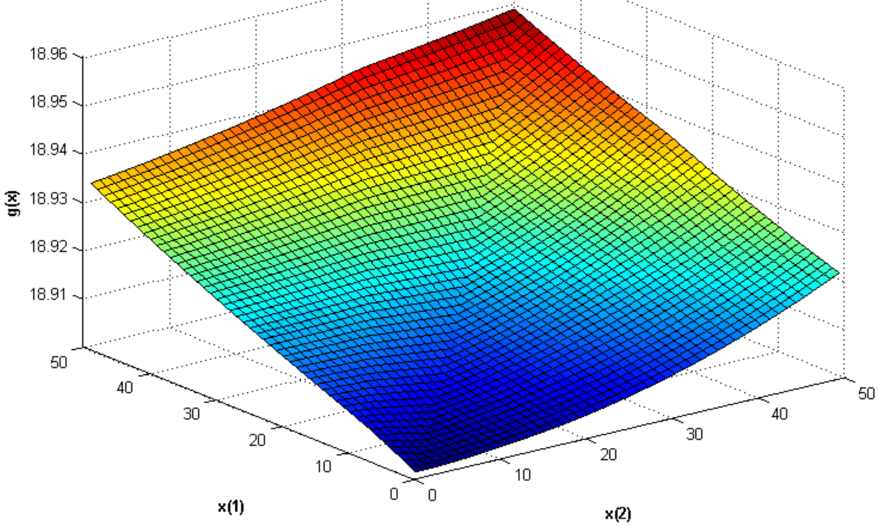
$$g(x) = \sum_{i=1}^{m} f_i^2(x)$$

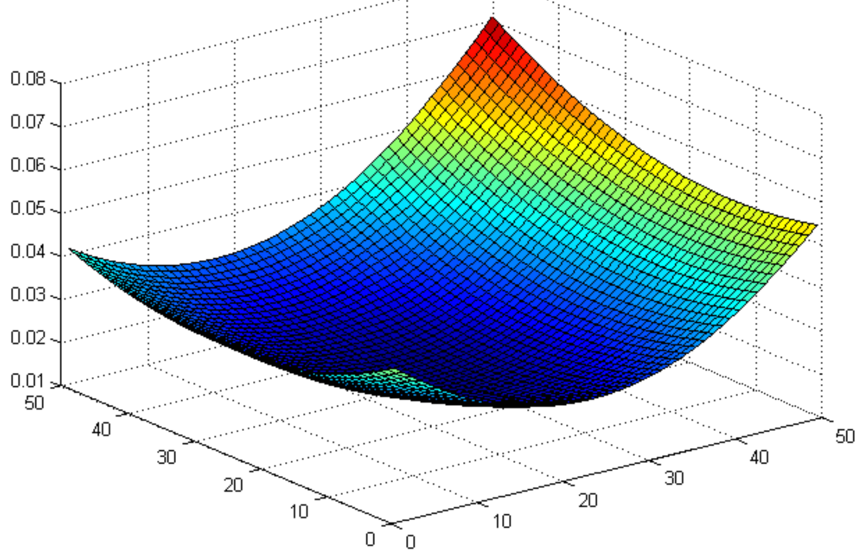
where

- x is a vector of n real parameters
- $f_i(x) = model(x, t_i) - measurement(t_i)$

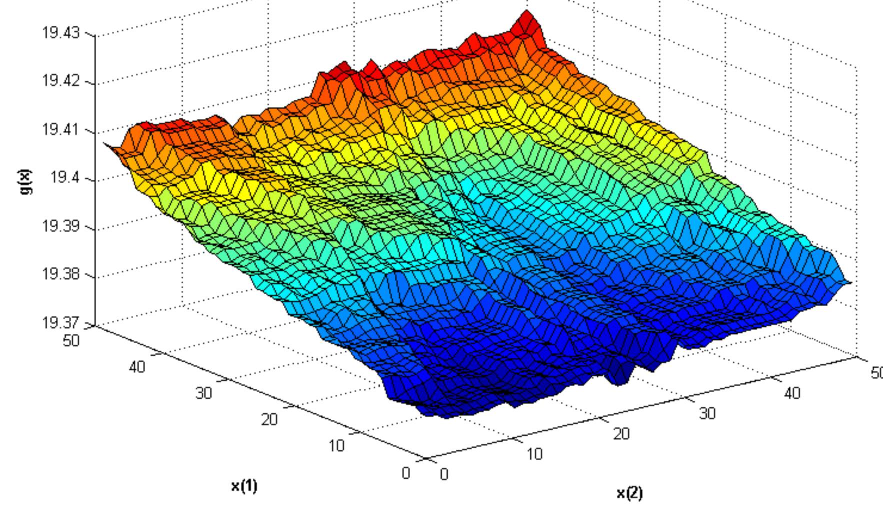
A problem with chip simulation

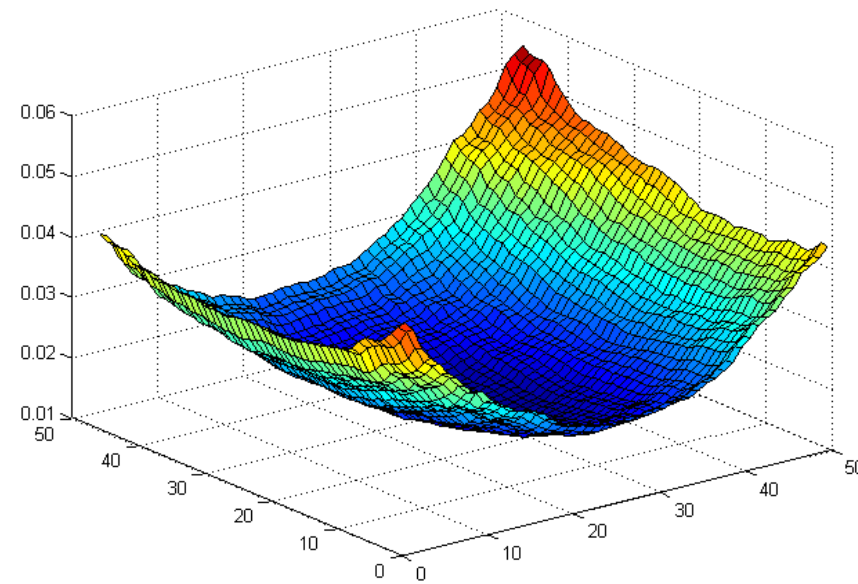
goal function: Simulink model





chip simulation

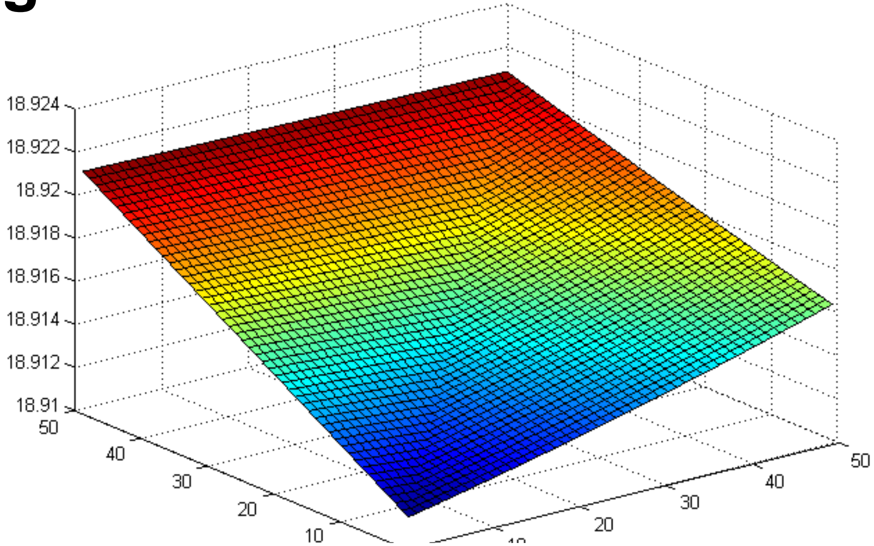


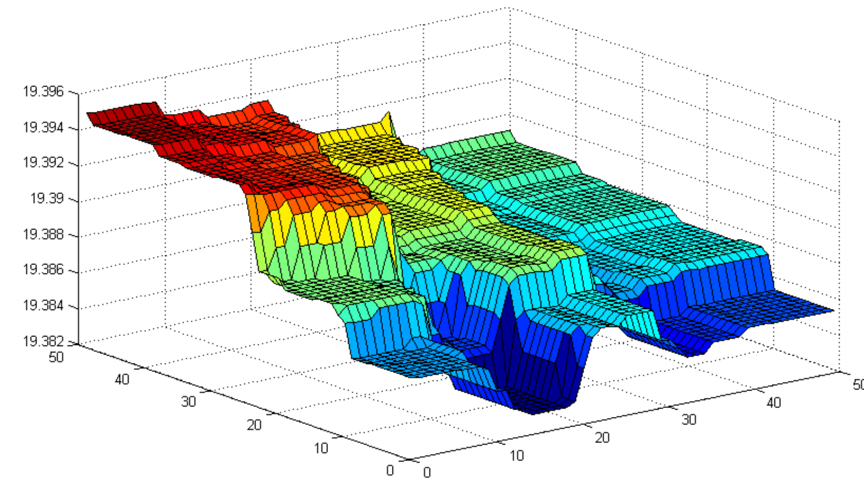


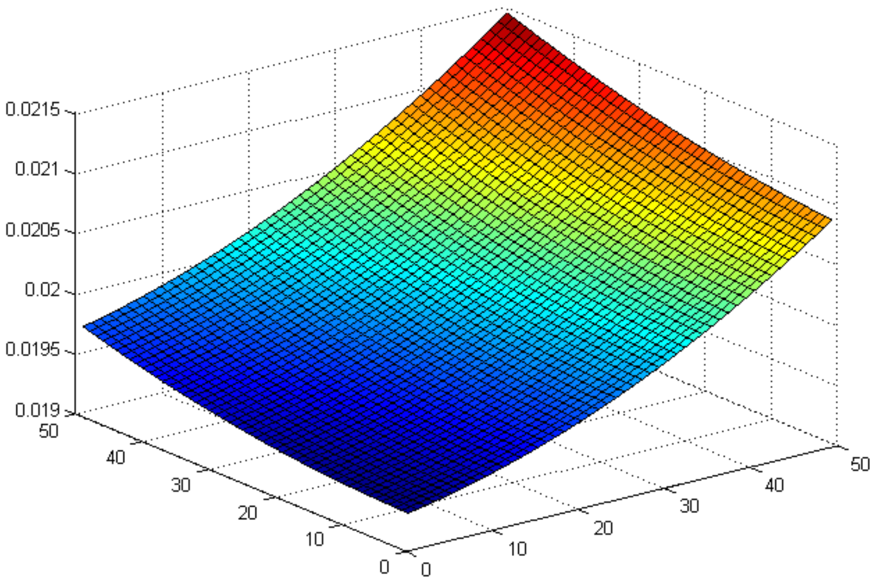
A problem with chip simulation

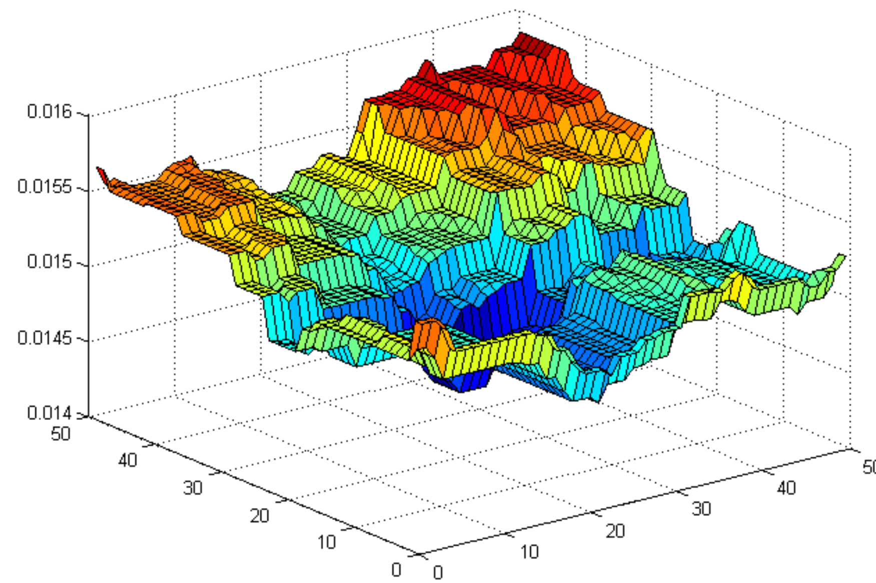
goal function: Simulink model

chip simulation









A problem with chip simulation

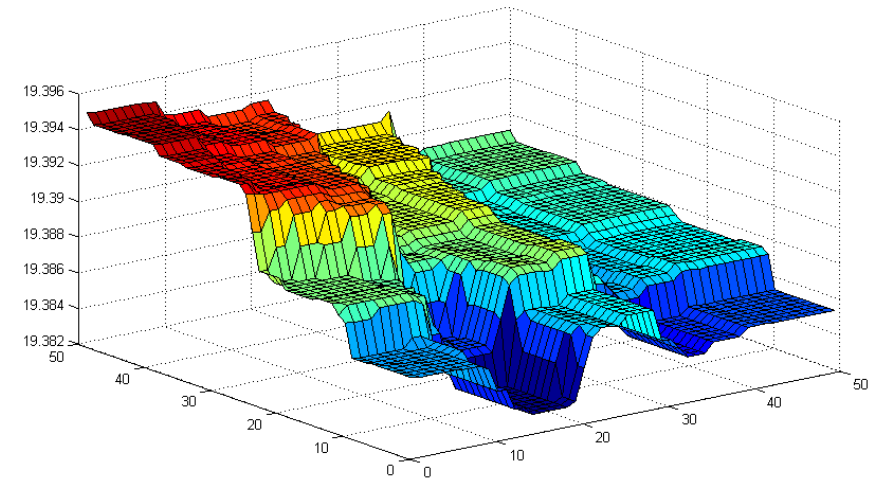
Optimization methods often require **gradients** to guide search

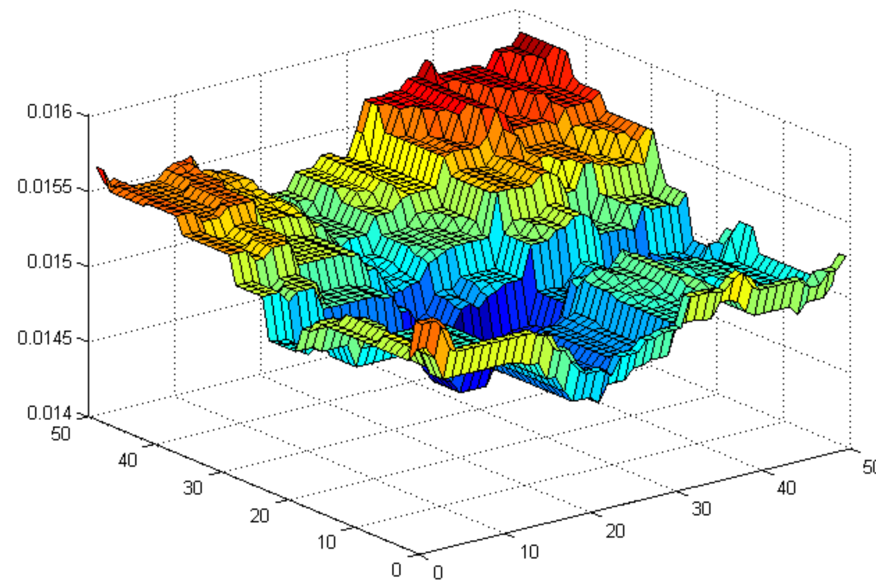
Engine control often implemented using **fixed-point integer** code

→ gradients of the goal function are zero (or undefined)

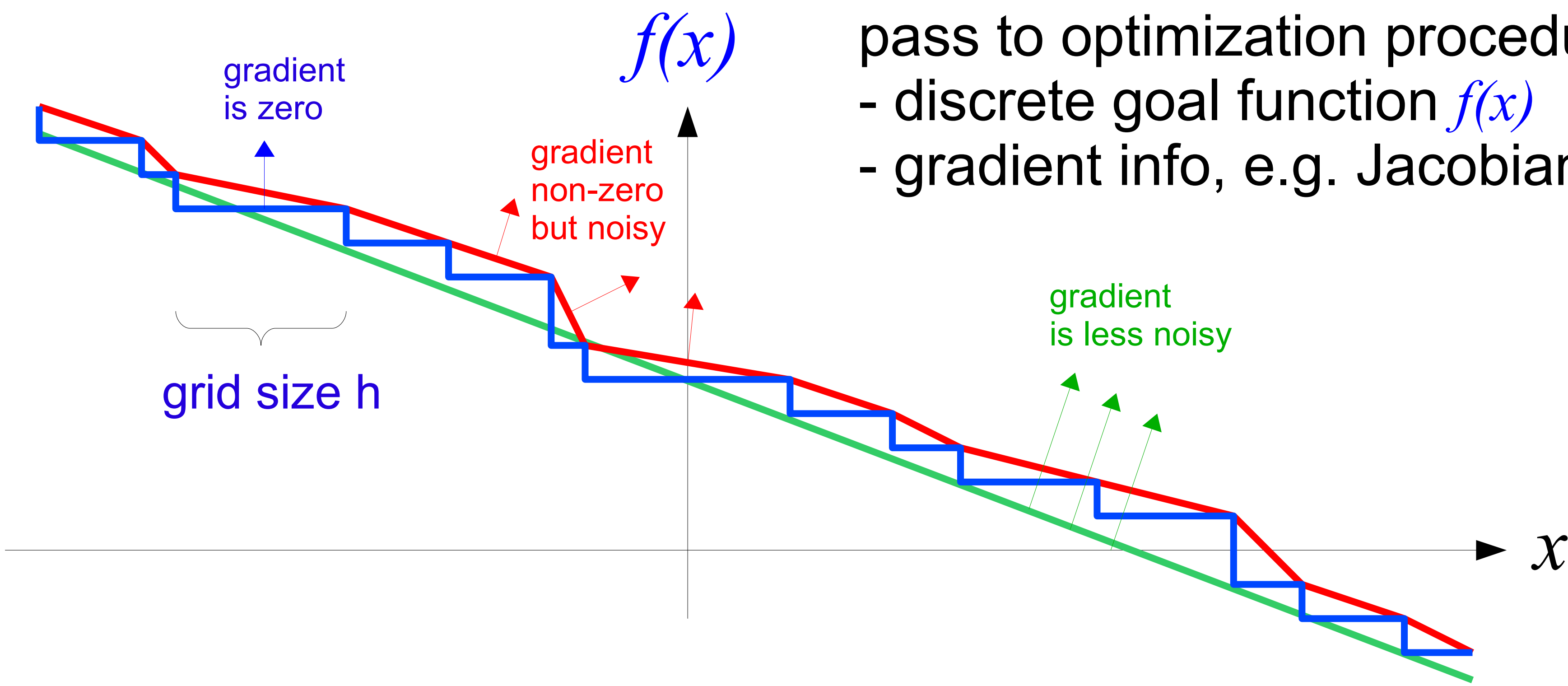
→ no guidance

→ optimization terminates early at local optimum





Idea 1: construct a smooth goal function



pass to optimization procedure
- discrete goal function *f(x)*
- gradient info, e.g. Jacobian *Jij*

f(x) goal function implemented using chip simulation: zero gradient

f(x) use current grid size h to compute gradient

$$\frac{f(x+h)-f(x)}{h}$$

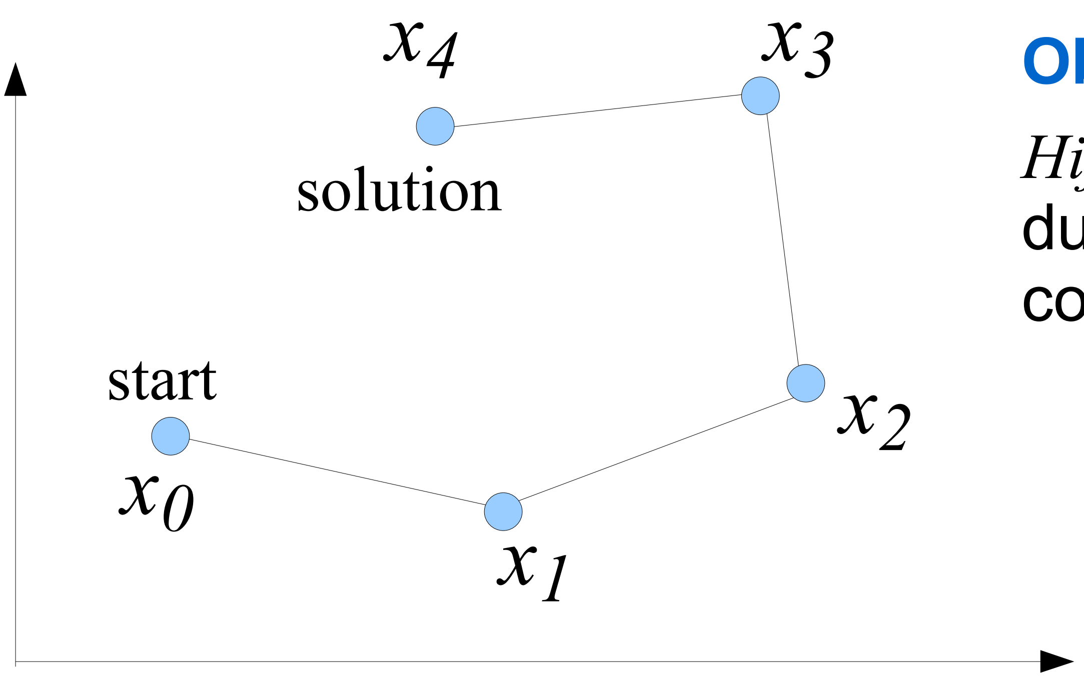
f(x) less noise: use 10 h to compute the gradient

Idea 2: pre-compute grid sizes

m time points, n parameter

→ m x n matrix Hij of grid sizes

→ must be computed at each step $x0$, $x1$, $x2$, ... expensive!



Observation

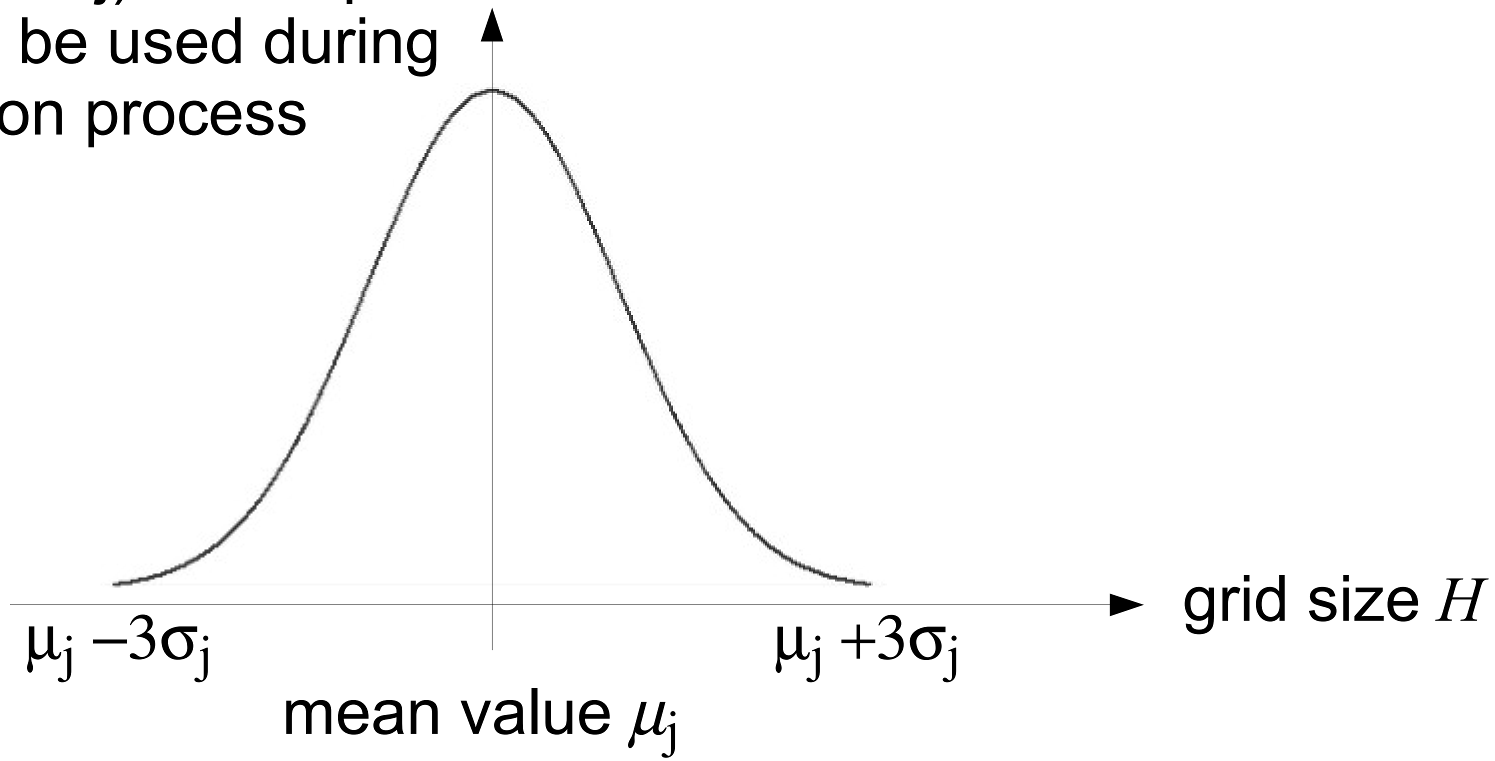
Hij does not change much during the solution process: compute only for $x0$ and reuse

Idea 3: Stochastic model of grid sizes

For large problems, do not compute all elements of matrix *Hij*

Use **stochastic model**: for parameter *xj*

- compute *Hij* for *x0* and some (not all) time points *ti*
- estimate **average** μj and **standard deviation** σj
- use $hj = 10\ (\mu j + 3\sigma j)$ to compute gradient of *xj* to be used during the entire solution process



Example: Tune engine model used by engine controller

- m = 202 measurement time points
- n = 20 parameters
- solver: **lsqnonlin** from MATLAB optimization toolbox
- goal function implemented using chip simulation
  - gradient info passed using option FinDiffRelStep
  - stochastic model of grid sizes
- performance validated against hand-coded smooth Simulink model
  - very **similar solutions** found
  - similar number of function evaluations
  - **factor 2 slower** with chip simulation, to compute grid sizes

Using Chip Simulation to Optimize Engine Control

- chip simulation can be used to port ECU functions to PC
- the resulting model
  - runs much faster than real time
  - can be coupled with optimization procedures to automate engine calibration
- derivative-free optimization: no problem
- otherwise: compute gradient as finite difference with controlled step size