Discrete control-based design of adaptive and autonomic computing systems

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Outline

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1. Adaptive systems
2. Autonomic and reactive systems
3. BZR language
4. Discrete feedback computing
5. Conclusion

Adaptive computing systems

two complementary, and sometimes contradictory, requirements:

- **adaptability** to changes in their environment or functionality
- **dependability** w.r.t. their goal and persons in contact

administration loops in computing systems

reacting to changes in:

- operation environment
- implementation platform
- application objectives

automated

too large or complex
sometimes too fast

for manual administration

⟶ **Autonomic Computing** : self-managed systems
automated administration in the form of a feedback loop

Control for dependability

- w.r.t. damage in system finality (information, business, ...)
- w.r.t. safety (goods, persons, ...)

specificity of autonomic systems : automated feedback loop

need for control of automated behaviors

- they can oscillate, diverge, react too slowly, ...
- objectives can be multiple and interfere

$\longrightarrow$ design theories and techniques from **Control Theory**

new interaction between control and computer science

- computer science for control systems : embedded systems
- theoretical informatics and control theory : hybrid systems

$\rightarrow$ **control theory for computing systems** considered here
for well-behaved automated computer management loops

Outline

1. Adaptive systems
2. Autonomic and reactive systems
    - Autonomic computing
    - Control for feedback computing
    - Reactive languages, verification and control
3. BZR language
4. Discrete feedback computing
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Autonomic computing

Autonomic Computing Initiative (ACI) initiated by IBM, early 2000

networked computing systems able to manage themselves, trough decisions made automatically, without direct human intervention

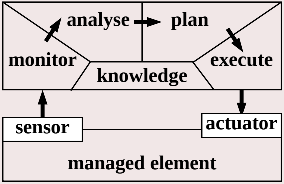
autonomic objectives

- Self-configuration
- Self-healing
- Self-optimization
- Self-protection

can interact, interferences can require coordination

autonomic loop

MAPE-K



Control for feedback computing

for guarantees on behavior of automated closed-looped systems

control theory: framework of methods and techniques

to build automated systems with well-mastered behavior

sensors and actuators connected to given "plant" to be controlled

model of the dynamic behavior of the process,

control objective specified explicitly

$\longrightarrow$ on these bases the control solution is formally derived

Control for computing systems: Feedback Computing

not usual in Computer Science, still only emerging

advantages: rigorous, supports uncertainties, stability, robustness,

difficulties: modeling and translating management objectives

to actual system-level sensors and actuators,

to appropriate, useable control models

most computing systems not designed to be controllable

Reactive languages, synchronous programming

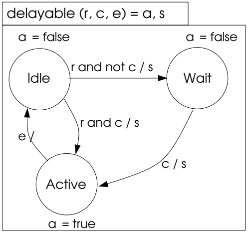
Modelling formalism **and** programming language

- reaction to input flows → output flows
- data-flow nodes and equations ; mode automata (FSM)
- parallel (synchronous) and hierarchical composition

synchronous languages, (25+ years)

tools: compilers (e.g., Heptagon), code generation, verification, ...

example: delayable task control (in Heptagon)



```
node delayable(r,c,e:bool) returns (a,s:bool)
let automaton
state Idle do
   a = false; s = r and c
  until r and c then Active
      | r and not c then Wait
state Wait do a = false; s = c
  until c then Active
state Active do a = true; s=false
  until e then Idle
end tel
```

Discrete controller synthesis (DCS): principle

Goal

Enforcing a temporal property Φ on a system
on which Φ does not yet hold a priori

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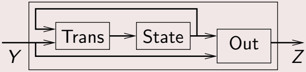
Principle (on implicit equational representation)

State	memory
Trans	transition function
Out	output function



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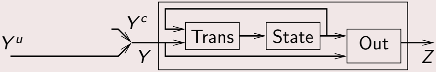

- Partition of variables : controllable (Y^c), uncontrollable (Y^u)

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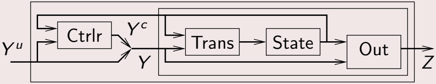

- Partition of variables : controllable (Y^c), uncontrollable (Y^u)
- Computation of a controller such that the controlled system satisfies Φ by control (invariance, reachability, attractivity, ...)

DCS tool: Sigali (H. Marchand e.a.)

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1. Adaptive systems
2. Autonomic and reactive systems
3. BZR language
   - The BZR language for tool-supported design
   - Modularity in BZR
4. Discrete feedback computing
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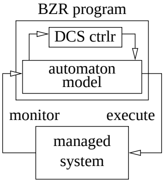
BZR programming language [`http://bzr.inria.fr`]

- built on top of nodes in Heptagon
- to each contract, associate controllable variables, local
- at compile-time (user-friendly DCS),
  compute a controller for each component
- when no controllable inputs : verification by model-checking
- *step* and *reset* functions ; executable code : C, Java, ...



```
node delay
  (new_sig: bool; c:bool)
returns (out: bool)
let automaton
  state Idle
   do out=new_sig & c
   until new_sig & not c
                then Waiting
    | new_sig & c then Idle
  state Waiting
   do out=c
   until c then Idle
end tel
```

```
node main
  (signal1, signal2: bool)
returns (d1, d2:bool)
contract
 enforce not (d1 & d2)
 with (c1,c2:bool)
let
 d1 = delay(signal1, c1);
 d2 = delay(signal2, c2);
tel
```

& *G. Delaval & H. Marchand* [ACM LCTES'10] [jDEDS13]

Need for modularity

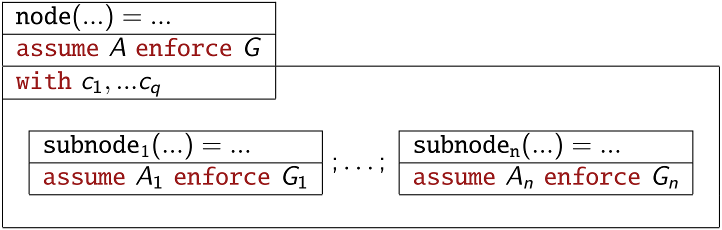
Advantages of DCS approach

- (i) high-level language support
- (ii) correctness of the controller,
- (iii) maximal permissiveness of controllers
- (iv) automated formal synthesis of these controllers
- (v) automated executable code generation in C or Java.

Need for modularity

- scalability: state-space exploration algorithms are exponential
- re-usability of management components

Modularity in BZR



node(...) = ...

assume A enforce G

with $c_1, ...c_q$

subnode$_1$(...) = ...

assume A_1 enforce G_1

; . . . ;

subnode$_n$(...) = ...

assume A_n enforce G_n

Modular contracts in Heptagon/BZR

based on the modular compilation of the nodes

- **assume** not only A, but also that the n sub-nodes each do enforce their contract: $\bigwedge_{i=1}^{n}(A_i \implies G_i)$.
- **enforce** G as well as the assumptions of sub-nodes: $\bigwedge_{i=1}^{n} A_i$

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   - General design method
   - Reconfiguration control in DPR FPGA-based architectures
   - Coordination of administration loops
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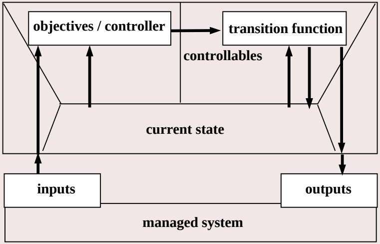
General design method

An interpretation of the MAPE-K loop



Typical modeled features

observability & controllability

resources: levels, on/off,

tasks: activity, start, end, checkpoints, modes

application: task graph, workflow

Granularity levels, depending on decision problem

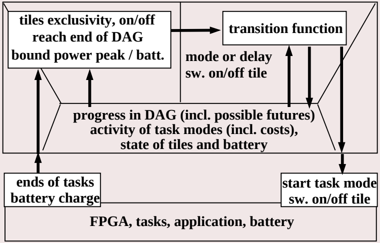
lowest : MEs : (relatively) fast, low overhead

level of AM : slower pace, sporadic ; limited by dynamics of system

level of AMs coordination : even slower, can afford synchronizations, distributed decisions e.g. leader election

Reconfiguration control in DPR FPGA-based architectures

Considered class of architectures ANR Famous



tiles exclusivity, on/off
reach end of DAG
bound power peak / batt.

transition function

mode or delay
sw. on/off tile

progress in DAG (incl. possible futures)
activity of task modes (incl. costs),
state of tiles and battery

ends of tasks
battery charge

start task mode
sw. on/off tile

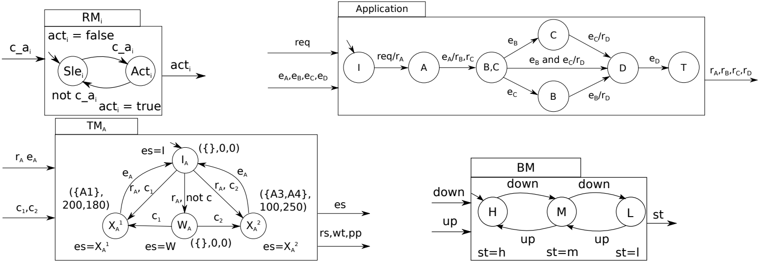
FPGA, tasks, application, battery

- **architecture** : tiles $A_{1..n}$, (sleep mode) ; battery
- **tasks** : delayable ; modes (tiles, power, WCET, ...)
- **application** : task graph

reconfiguration policy

1. resource usage : exclusive tiles $A1$-$A4$
2. energy : tiles active if and only if needed
3. power peak : bounded w.r.t battery level
4. reachability: application graph end
5. optimizing e.g., global power peak

Modelling for in DPR FPGA control [ICAC13]



Generic models

tiles RM_i, task graph, (two-modes) tasks, battery

global model : composition of instances

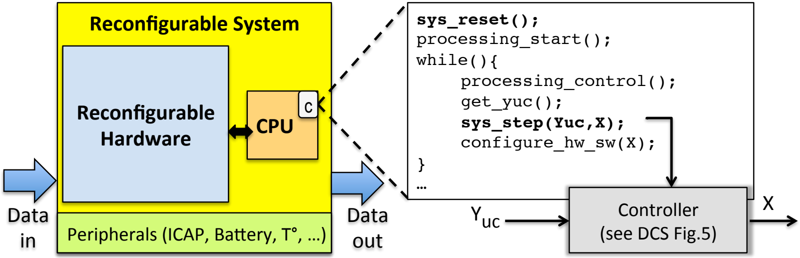
reconfiguration policy

Objective 1 to 3 : *invariance* e.g., for 3 :

$$PP < (v_1 \text{ if } st = h \text{ else } v_2 \text{ if } st = m \text{ else } v_3 \text{ if } st = l)$$

Objective 4 : *reachability* of terminal state T

Implementation of DPR FPGA control



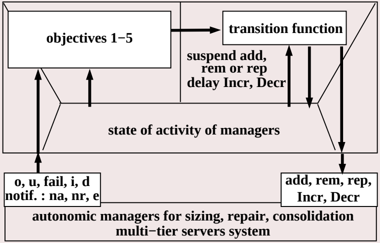
```
sys_reset();
processing_start();
while(){
    processing_control();
    get_yuc();
    sys_step(Yuc,X);
    configure_hw_sw(X);
}
…
```

calling executable code generated by BZR

- call **reset** function to initialize sates
- loop for cyclic reaction :
  - acquire sensor input
  - construct automaton input Yuc
  - call **step** function to make transition and decisions
  - transform automaton ouput X into calls to OS API (start, ...)

Coordination of administration loops

Administration loops and their coordination ANR Ctrl-Green



objectives 1−5

transition function

suspend add,
rem or rep
delay Incr, Decr

state of activity of managers

o, u, fail, i, d
notif. : na, nr, e

add, rem, rep,
Incr, Decr

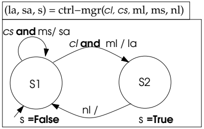
autonomic managers for sizing, repair, consolidation
multi−tier servers system

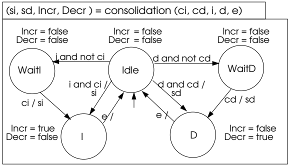
- **multi-tier applications** : replicated web servers ; load balancers
- **autonomic managers** : Self-sizing ; Self-repair ; Consolidation
- **problems** : over-reaction

reconfiguration policy

1. In a replicated tier, avoid size-up when repairing
2. avoid size-down in successor tier when repairing predecessor
3. when consolidating, avoid self-sizing or repairing

Modelling for coordination control [jFGCS14]





Generic models

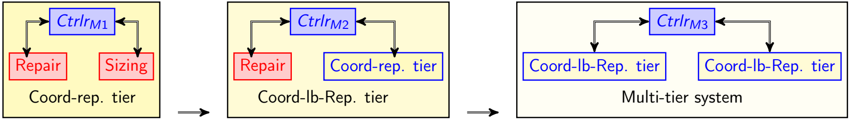
Self-sizing control
Self-repair control
Consolidation control

models instantiated for each AM
composition gives global behavior

reconfiguration policy

① not (repairing and add)
② not (repairingL and rem)
③ not (repairing$_{pred}$ and rem$_{succ}$)
④ ...

Modular coordination control [CBSE14]



Bottom-up re-use of nodes

- **replicated servers** tier: `Coord-rep. tier` coordinating one Repair and one Sizing
- **load-balanced** tier: `Coord-lb-Rep. tier` coordinating one Repair (for LB) and one of the former
- **application**: `Multi-tier system` coordinating two of the former

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   - & perspectives

Conclusions & perspectives

Results

overview on discrete control-based design of autonomic computing

- **tool-supported** method, reactive language & discrete control
- **validation** in domains from software components and smart environments to hardware reconfigurable architectures.
- control-based techniques offer, at the same time, **self-adaptation and predictability**

Perspectives

- **Modeling** : other aspects of computing systems (memory, ...)
- **Expressivity and scalability** : logico-numeric
- **High-level languages** : Domain Specific Languages (DSLs)
- **Adaptive discrete control** : not much theory yet