Conquering MPSoC Design and Architecture Complexity with Bio-Inspired Self-Organization

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The System Design Complexity Challenge
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- Moore’s law is the technological enabler for Billion MOSFET designs, but …
  - … how to deal with the design complexity of Billion MOSFET (MP)SoCs
  - considering implications of various forms of variability
  - and get the design and fabrication right at first time?
- When the MPSoC design & manufacturing challenge is solved, how to …
  - program massively parallel processor components,
  - guarantee real-time, security, mixed-criticality and power constraints?
- Progress of IC design and integration gets more and more constraint by direct or indirect complexity issues
- What alternative to established, best practice engineering approaches do we have to tackle complexity?

MPSoC Resilience

- Video frames distributed among 1 – 3 operational RISC cores
- RISC cores may arbitrarily fail … (mimicked by purposely switch-off every few 100 ms)
- … which is compensated by workload redistribution and $f, V_{DD}$ scaling (DVFS) of remaining cores
- Heuristic by which $f, V_{DD}$ are altered will be revealed later
The more often we switch cores off/on, the lower the frame drop rate.

MPSoc Task Mapping / Workload Balancing

- IP packet processing is split into 5 tasks, which are executed sequentially and initially all mapped to Core 1
- IP flow received at MAC, sent to T1 and received from T5 for retransmit
- Cores may issue task relocation when in high-load condition and perform DVFS
- Same heuristic and method applied as in previous example of resilient video applications
With increasing number of packets received / processed, the core utilization saturates at high, frequency at low level.

... and variation of IP packet forwarding latency settles at low level.
"Manycore" System in Nature …

- Fish school does not seem to have a complexity or reliability problem
- Entire system behaves orderly and defends itself reliably against predators
- How is orchestration of “fish school” facilitated among its components?

If \( d < R_r \) then
Repulsion: Avoid clashes
Else if \( d < R_p \) then
Orientation: Parallel to neighbor
Else if \( d < R_a \)
Attraction: Approach companion
Endif

Nature designs and optimizes differently … [Inada02, Pathel04]

Every system constituent (fish) follows a local rule set on how to behave under stress
- Rule set is simple, easily manageable for each constituent
- Every constituent follows same rule set
- Global system behavior not necessarily reflected in local rule set
Self-Organization / Emergence

Local behavior of the constituents of a self-organizing system may lead to observable, emergent global behavior which is not reflected in local behavior / rules

- **Population** of interacting system constituents
- System is hierarchically structured (multi-layer organization)
- **Emergent behavior** observable at levels above constituent level (system level or system environment) as a result of hidden causal relationships across levels

Conway’s Game of Life

Constituent pattern determines system level behavior:

- Rotary, translatory movements, oscillation, persistence, …
- … in combination and with varying parameters

If (cell alive AND N = 3) then live unchanged to next generation
Else if (cell alive AND N < 2 OR N > 3) then death by loneliness or overcrowding
Else if (cell dead AND N = 3) then birth of new cell in next generation
End
ASoC: Autonomic System on Chip

Evolutionary, platform-centric approach with compatibility to SoC design method:
- Functional layer containing conventional IPs
- Autonomic layer extends IPs with self-x properties
  - Improved Reliability
  - Performance / Power optimization at runtime

Dedicate part of chip capacity to self-x abilities at autonomic layer

Future SoC shall have the ability to learn to live with environmentally imposed variations or work around defects autonomously

A. Herkersdorf

ASoC: Self-Optimization through Runtime Learning

- **Monitors**
  - Error rate, (Temperature)
  - Frequency
  - Utilization
  - Workload

- **Actuators**
  - Frequency (and voltage)
  - Task migration

- **Evaluator**
  - Learning classifier system adapted for efficient HW implementation
  - Reinforcement learning through fitness update of individual rules

- **Communicator**
  - Sharing of global information

Learning Classifier Table:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Action</th>
<th>Fitness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 X X 0 X</td>
<td>1001</td>
<td>1010</td>
</tr>
<tr>
<td>X 0 1 X</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>X 1 0 X</td>
<td>1100</td>
<td>15</td>
</tr>
</tbody>
</table>

Fitness Update

Joint project with University of Tübingen and FZI Karlsruhe
ASoC: Self-Optimization through Runtime Learning

- Fitness-driven rule and operation parameter selection per core
- Objective function to assess system-wide impact of rule/action selection:
  \[
  \delta_{\text{Load}} = |f_{\text{cpu}n} \cdot \text{util}_{\text{cpu}n} - f_{\text{cpu avg}} \cdot \text{util}_{\text{cpu avg}}| \\
  \delta_{\text{Util}} = \text{util}_{\text{target}} - \text{util}_{\text{cpu}n} \\
  \delta_{\text{Freq}} = f_{\text{cpu}n} \\
  O_{\text{CPU}} = w_1 \cdot \delta_{\text{Load}} + w_2 \cdot \delta_{\text{Util}} + w_3 \cdot \delta_{\text{Freq}} \\
  O_{\text{Sys}} = w_4 \cdot O_{\text{CPU1}} + w_5 \cdot O_{\text{CPU2}} + \ldots
  \]
- Reward function:
  \[
  R(O) = \begin{cases} 
  +N & \text{if } O > O_{T-1} \\
  -N^2 & \text{if } O < O_{T-1} 
  \end{cases}
  \]

[Zeppenfeld11]
ASoC: Self-Optimization through Runtime Learning

Fitness separation between more and less effective rules / actions (replacing evolution in nature)

Exploration / adaptation within identified rule set to possibly adopt a global optimum

LCT / AE Implementierung

<table>
<thead>
<tr>
<th></th>
<th>Flip-Flops</th>
<th>LUTs</th>
<th>BRAMs</th>
<th>Mult.</th>
<th>Overhead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leon3</td>
<td>1749</td>
<td>8936</td>
<td>28</td>
<td>1</td>
<td></td>
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<tr>
<td>Leon3 AE</td>
<td>2122</td>
<td>10213</td>
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<tr>
<td>LCT</td>
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<td>116</td>
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<td>1</td>
<td>1.4%</td>
</tr>
<tr>
<td>Act Task.</td>
<td>57</td>
<td>299</td>
<td>0</td>
<td>0</td>
<td>3.5%</td>
</tr>
<tr>
<td>ActFreq.</td>
<td>7</td>
<td>19</td>
<td>0</td>
<td>0</td>
<td>0.2%</td>
</tr>
<tr>
<td>Mon Util.</td>
<td>35</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>Mon Load</td>
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<td>0</td>
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<tr>
<td>AE IF</td>
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<td>399</td>
<td>0</td>
<td>0</td>
<td>4.5%</td>
</tr>
</tbody>
</table>

Synthesis results for Xilinx Virtex 4 VLX100
Conclusions

- Complexity of multi-objective hardware/software systems demands push of classical design time tasks into field operation
  - Complexity either increases through technology-enabled increases in function integration or consideration of pressing non-functional aspects
    - Security, resilience, power dissipation, test & debug
- Nature offers scalable, surprisingly simple self-organization paradigms to control complex systems
- Suggestion to study and apply emergent behaviors on broader scope for optimization of non-function aspects of MPSoC and distributed Embedded Systems / CPS
- Be inspired by nature, but also be aware that …

... copying nature 1-on-1 not necessarily yields success!

"Kleiner Schlagflügelapparat", 1893

"Der Vogelflug als Grundlage der Fliegekunst", O. Lilienthal, 1889

Thanks!

“All arts rely on mimicking nature.”

Seneca (1 – 65 AD), roman philosopher, scientist, politician

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References


[Herkersdorf04] Herkersdorf, A., Rosenstiel, W., "Towards a Framework and Design Methododology for Autonomous SoC”, GI Workshop on Organic Computing, Ulm, Germany, September 2004


References

