Life-Inspired Systems

Lech Jóźwiak
Eindhoven University of Technology
Faculty of Electrical Engineering
L.Jozwiak@tue.nl

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Outline

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4. Conclusions
What system design is about is a definition of the required quality, in the sense of a satisfactory answer to the following two questions:

- What (new or modified) quality is required?
- How can it be achieved?

Design, being a definition of the required quality, expresses:

the values, aims and quality of life of a particular society having a particular culture, technology, and functioning in a particular space, time, and conditions.

What is perceived as quality depends on:

social, cultural and other aspects, and in particular, value systems and material culture, specifically: technology.
Societies, their value systems, cultures, and technologies evolve

↓

*the quality of the future is different than the quality of the past.*

**Systems of the past:**

- based on the matter and energy processing
- concrete/material
- static
- simple behavior
- objects

**Systems of the future:**

- based on the information processing
- abstract/ideal/virtual
- dynamic
- complex and intelligent behavior
- subjects/persons
To ensure that these new systems will represent the actually required quality, their designers must well understand and adequately account for:

- the rapidly changing information-based technology,
- the more and more complex and quickly evolving organization, culture, value systems and actual needs of the society.

The recent rapid progress in microelectronic technology that enabled SoCs and SiPs created new important opportunities, but also new serious difficulties resulting from:

- the huge and rapidly growing silicon and system complexity, and
- the remarkable and growing role of the information technology systems.
An adequate solution of these problems can only be achieved through development and application of more suitable system and design paradigms, methods and means.

This presentation aims at:

- a brief analysis of the current situation, future trends and problems in the field of the modern microelectronic-based systems, and
- discussion of a new system paradigm of the life-inspired systems.
The progress in microelectronic technology is extremely rapid:  

- a new technology generation replaces the current one every two-three years  
- the memory capacity grows four times from generation to generation  
- the microprocessor and ASIC complexity grows three times, and  
- the prices of the memory bit and logic gate decrease 2.4 times.
Modern microelectronic technology enables implementation of complete complex information processing systems on a single chip, including analog and digital hardware and embedded software.
Modern microelectronic technology

- Microelectronic technology will be further developed and used for the next decades:
  - MOSFETs with 90 nm gate length have been introduced to the production, but the sub-10 nm MOSFETs are in the labs, and a 5nm MOSFET has been reported a year ago
  - physical limits will not be reached soon (50 years)
  - supposing a new competing technology will be developed (e.g. photonic, atomic or biological (DNA-computing)), it will take at least 10-20 years until this technology will be matured and economically justified

- During the last 40 years, the semiconductor industry showed stable and much higher growth of the sold production than any other production branch, being as high as 15%, by fast dropping prices of microelectronic circuits (e.g. memories or microprocessors)

- Similar general growing trend is predicted to continue for the next decades, despite the recently passed crisis conditions
Sales on the world-wide semiconductor market (2001)

Source: Gartner
The **SoC technology, wire-less communication, and global networking**:  
- make completely *new sorts of systems technologically feasible and economically justified*, especially for applications that require miniaturization, high performance, low power dissipation, and wire-less or distant communication.  
- created a *big stimulus towards development of various kinds of application-specific embedded systems*, including ambient intelligence, augmented reality, and ubiquitous, wearable or even implanted computing.  

**Example**: Various *measurement, control, diagnostic, stimulation, computing and communication systems* that can be put on or **embedded** in mobile objects, installations, machines, devices, home equipment or even implanted in human or animal body (for instance: intelligent shoe of Adidas, Philips wearable devices and other ambient intelligence cases).
An **embedded system** (unlike a stand-alone computer) is an *inseparable part of a certain larger system*.

It is built in this larger system and designed especially or adapted to serve a specific aim in this system, for instance: measurement, control, information processing or communication.

Typically, **embedded systems**:

- are *reactive real-time systems*
- include **sensing, interfacing, processing and actuating** sub-systems, and
- involve in their implementation various **mixtures of digital and analog hardware and software**.
- **Embedded systems** play a **remarkable role** in today's life and are **used in virtually all fields**:
  - at home - in every day appliances and home electronics
  - in office - inside of the office automation equipment
  - in hospital - inside of medical devices
  - in factory - in robots and machines
  - in plane - as parts of various control and navigation systems
  - in car - in suspension, engine, brakes and door controllers, etc.

- They are **very difficult to design, implement and validate**:
  - their design is highly innovative (application-specific)
  - must continuously communicate with their surroundings and appropriately react in real-time to the signals from the surrounding
  - are complex and heterogeneous
  - must satisfy various constraints and objectives specific for a certain application
  - many of them are used in critical applications that impose **extremely high quality requirements**.
The **spectacular advances in semiconductor technology** that enabled **SoCs and SiPs:**

- opened *much better ways to serving existing applications*
- made *possible and affordable numerous new applications*, especially related to application-specific embedded systems, mobility and wireless or distant communication.

They introduced **unusual complexity:**

- **Silicon Complexity**
  - large number, diversity, small dimensions and huge density of devices and interconnects
  - huge length of interconnects and variety of new device/interconnect architectures
  - new materials and mixed technologies

- **System Complexity**
  - huge number of possible system states
  - large number and diversity of subsystems
  - extremely complex interactions and interrelations between the subsystems.
Due to the **Silicon Complexity**, and especially:

- extremely high device densities,
- extremely small devices’ physical dimensions,
- power supply reduction, and
- very high operating frequencies

many previously ignorable phenomena have a **great impact on the system correctness and other quality aspects**.
The Silicon Complexity results in a number of new difficult to solve issues:

- power and energy crisis, and fluctuations in power density distribution
- exponential increase in leakage power
- substrate coupling and delay variation due to cross-coupling
- on-chip communication and synchronization problems
- decreased reliability (noise, interference, signal integrity problems, increased defect density, manufacturing process variability, gate insulator tunneling, joule heating, electromigration, single event upsets and transients etc.)
- decreased design predictability
- manufacturability problems, and decreased yield
- high manufacturing (mask and probe card) NRE and production costs, etc.
The **System Complexity** also results in **a number of challenges**:

- design of complex and highly heterogeneous systems with exponentially growing number of states
- ensuring quality and validation (simulation, formal verification, testing etc.) of such complex and heterogeneous systems with exploding number of states and components,
- ensuring their responsiveness, reliability and safety in the light of changing, noisy and unreliable environment and interior
- reducing the design productivity gap and shortening time-to market
- reducing the design NRE costs.
The microelectronic-based systems:

- are used in virtually all sorts of technical and social systems, in more and more important and demanding applications, and even implanted in our bodies
- influence our life to a higher and higher degree
- the society expectations regarding them grow rapidly
- become more and more often goal of various attacks and unauthorized manipulations by individuals and organizations
- will inherently be less reliable and more sensitive to noise and interferences with their environment.

Therefore, responsiveness, robustness and dependability of systems, as well as, reliable and secure sensing, storage, transmission and processing of information are critical to governments, organizations, businesses and individuals all over the world.
Many systems, and especially, many social systems, were developed not having in mind the extensive usage of the IT:

- they often cannot sufficiently profit from the IT
- the IT application may even result in their worse functioning or corrupt their stability.

The co-development of the mixed social, technical and/or biological systems is necessary.

The development of the future systems should aim at:

- the quality maximization of the total systemic solution,
- with a special focus on the stability, robustness, responsiveness, dependability, safety, security, adaptability, and validation aspects.

These aspects are not new and were considered in the past.

What is thus new or different now?
The different character of the current and future situation includes the following:

- due to the huge and growing silicon and system complexity, danger of attacks and manipulations, and more and more demanding applications, it will be more and more difficult to guarantee the systems’ quality

- due to the common usage of the IT systems in various kinds of social, technical and biological systems, the whole life on the Earth more and more depends on them:
  - their quality, and specifically responsiveness, dependability, safety and security are more and more critical to governments, organizations, businesses and individuals
  - the individual and society expectations regarding the system quality grow rapidly

- the share and number of critical applications will grow, also applications considered previously as non-critical will become critical, because we more and more rely on them.
In the future systems:

- the features, like high responsiveness, dependability, robustness, safety or security will become more common, even in relation to the so called consumer applications (e.g. mobile phones or PCs)
- due to their common character, reasonably low-cost solutions must be used
- these features cannot anymore be added on the top of the designed system, when using simple, but expensive solutions, but must be:
  - accounted for from the very beginning of the system specification and design process
  - implemented using sophisticated, effective and efficient solutions
  - considered in parallel with all other important system aspects to share the implementation costs for various features and account for the consequences of their implementation for another required system characteristics.

This will:
- allow for an adequate tradeoff exploitation and multi-objective optimization
- result in more coherent, compact, comprehensive, reliable, robust and lower-cost solutions.
The transition from:

- **multi-chip systems** to **systems-on-a-single-chip**
- **general-purpose stand-alone computers** to **application-specific embedded systems**
- **separated systems** to **networked systems**
- **wire-based communication** to **wireless communication**
- **static systems** to **mobile and dynamic systems**

is not a gradual change, but a real **paradigm shift**: 

- it opens new possibilities
- creates new very serious difficulties

that cannot be adequately resolved without an **adequate system and design methodology adaptation**.
The **adequate system paradigm** and **design paradigm** to solve the problems seem to be the paradigms of:

- **quality-driven design**, and
- **life-inspired systems**.

During the last ten years, we researched the **methodology of quality-driven design** in application to:

- architecture synthesis, multi-objective hardware/software partitioning and mapping of the generic platform-based hard real-time embedded SoCs, and
- multi-objective optimal circuit synthesis.

Recently, I proposed the **paradigm of the life-inspired systems** that we are currently researching.

*What are the life-inspired systems?*
The **paradigm of life-inspired systems** originates from the observation that:

- **the complexity, operation domains and roles of the microelectronic-based systems**

  more and more resemble

- **the complexity, operation domains and roles of the (intelligent) life organisms**.

Based on this parallel, I formulated the **hypothesis** that:

- **the future microelectronic-based systems should have characteristics that resemble the characteristics of the (intelligent) life organisms**.

Cosequently:

- **the basic concepts, principles, functional and structural organization etc. of the microelectronic-based systems should resemble these of the (intelligent) life organisms.**
Like a real organism, the life-inspired system should be a largely autonomous, self-contained, robust, dynamic, self-organizing, self-adapting, self-regulating evolutionary system.

Like a real organism, it should be composed of largely autonomous, diverse, having their own particular aims and optimized for these aims sub-systems (organs or centers)

The sub-systems should be:
- adequately (hierarchically) organized
- interconnected with an appropriate network of communication channels
- properly coordinated and adequately collaborating with each other to synergistically achieve the global system aims.

REMARK: This is thus a very different view of the self-organizing, self-adapting, self-regulating evolutionary system than the simplistic view of the flat, homogeneous and structurally-limited neural networks.
Similarly to the real brain, the **life-inspired system** should:

- not limit itself to the **traditional basic functions of an information technology system** of collecting, transmitting, storing, processing, and presenting information in relation to some external systems, but
- solve complex problems, take and implement difficult decisions, learn, discover new ideas, etc.

also **in relation to itself**.

To **achieve these diverse aims effectively and efficiently**:

- in relation to **complex applications**
- in the light of **changing, noisy, unreliable and dangerous environment and own interior**

the **life-inspired system** must include:

- largely autonomous diverse subsystems specialized to different aims
- adequate **self-protection, self-testing, self-diagnosis, self-repair, fault-tolerance and other adaptation mechanisms**.
Complex information processing is realized as a combination of simpler processing tasks that often can be performed in parallel:

- either using some single task-specific operators
- or long sequences of some “general-purpose” operators from some limited (close to minimal) functionally complete systems of operators.

The traditional von Neuman like sequential computers, by using the “general-purpose” operators and performing the processing basically sequentially in time, use a lot of time and energy comparing to the parallel systems that use the efficiently (in hardware) implemented task-specific operators and perform the processing tasks in parallel.

The sequential and CPU-centric processing results in memory and communication bottlenecks.
To avoid the memory and communication bottlenecks, processing time and energy inefficiency etc.:

- **information, intelligence and computational resources** of the life-inspired system should be properly distributed over all its sub-systems
- **effective application-specific operators** should be used
- **parallel processing should be applied** for tasks involving parallelism.

This requires:

- **local distributed memories** for the sub-systems
- **(more) global multi-port memories** for sharing data and communication between the sub-systems
- **memory-centric processing** for massive data - computations must come to data: **re-configurable computing**
- **(massively) parallel processing sub-systems** involving **application-specific in hardware implemented operators**
- **re-configurable hardware** to implement the **application-specific (parallel) processing and memory-centric processing effectively and efficiently.**
Life-inspired Systems

- **Re-configuration** will serve numerous purposes:
  - memory-centric processing for massive data
  - computation speedup, as well as, power and energy usage reduction in comparison to software solutions
  - design reuse and resource sharing
  - flexibility, adaptability, product differentiation
  - self-organization, self-regulation and adaptation in reaction to changing and unreliable surrounding and own interior, including fault-tolerance, self-protection, self-testing, self-diagnosis and self-repair
  - reducing the design productivity gap
  - shortening the time-to-market
  - reducing the design NRE costs.

- **Generic solution structures and architectures**, and particularly, the **generic system platforms** and **architecture templates** will serve similar purposes, and enable the **(semi-)automatic architecture synthesis, system partitioning and mapping**.
The life-inspired systems will also require for their adequate realization:

- new more **effective and efficient design methods and EDA tools**:
  - adequately addressing the new important design issues,
  - involving the quality-driven multi-objective design decision making, and
  - enabling higher design effectiveness and efficiency due to automation

- an **adequate mixture of design reuse** at the system and sub-system levels
  with **automatic synthesis** from the system or sub-system levels.
The paradigm of the *life-inspired systems* seems to be adequate to tackle the problems of the emerging technologies and of the new demanding applications.

This paradigm:
- unifies and combines many valuable concepts and approaches of the modern microelectronic system engineering, and
- explains what purposes these concepts and approaches can serve, and why are they useful.

Its application in combination with the *quality-driven design* should result in higher quality of systems due to:
- usage of systemic solutions more adequate in the context of the emerging and future technologies and new demanding applications, and
- a more coherent, systematic, effective and efficient design process.

I hope that the discussion of the:
- situation, trends and problems in the area of the microelectronic systems, and
- paradigm of the life-inspired systems will suggest many interesting research subjects important for the successful development and application of the future systems.