“Complex Systems and Control: The Paradigms of Structure Evolving Systems and Systems of Systems”

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Extended Abstract
Complex Systems is a term that emerges in many disciplines and domains and has many interpretations, implications and problems associated with it. The specific domain provides dominant features and characterise the nature of problems to be considered. A major classification of such systems are to those linked with *physical processes* (physics, biology, genetics, ecosystems, social etc) and those which are *man made* (engineering, technology, energy, transport, software, management and finance etc) and deal with the *“macro level”* issues and technology. Each of the above classes has its own key paradigms, specific problems, concepts and methodologies. There exist however generic common issues amongst the different domains and this requires the development of generic methodologies that can be applied across the different domains. Systems and Control concepts and tools are important in the development of methodologies aiming for the *Management of Complexity.*

Existing methods in Systems and Control deal predominantly with fixed systems, where components, interconnection topology, measurement-actuation schemes and control structures are specified. Two new major paradigms expressing forms of engineering complexity are:

- *Structure Evolving Systems (SES)*
- *Systems of Systems (SoS)*

The common element between those two new paradigms is that the interconnection topology may vary, evolve in the case of *SES*, whereas in the case of *SoS* the interconnection rule is generalised to a new notion of a “system play” [1], [2]. Here we are dealing with the fundamentals as far as representation, and structure, of those two classes and demonstrates the significance of traditional systems and control theory and introduces a control research agenda for those two complex systems paradigms. In fact:

Structure Evolving Systems [3]**:** Such a class of systems emerge in natural processes such as Biology, Genetics, Crystallography etc; the area of man made processes includes Engineering Design, Power Systems under de-regulation, Integrated Design and Re-design of Engineering Systems (Process Systems, Flexible Space Structures etc), Systems Instrumentation, Design over the Life-Cycle of processes, Control of Communication Networks, Supply Chain Management, etc. This family departs considerably from the traditional assumption that the system is fixed and its dominant features relate to:

■The topology of interconnections is not fixed but may vary through the life-cycle of the system (*Variability of Interconnection Topology Complexity*).
■The system may evolve through the early-late stages of the design process (*Design Time Evolution).*
■ There may be Variability and/or uncertainty on the system’s environment during the lifecycle requiring flexibility in organisation and operability (*Lifecycle Complexity*).
■ The system may be large scale, multi-component and this may impact on methodologies and computations (*Large Scale – Multi-component Complexity*).
■ There may be variability in the Organisational Structures in response to changes in goals and operational requirements (*Organisational Complexity Variability*)

The above features characterise a new paradigm in systems theory and introduce major challenges for Control Theory and Design and Systems Engineering. There are different forms of structure evolution. Integrated System Design has been an area that has motivated some of the early studies on *SES.* The integration of traditional design stages [4], such as Process Synthesis *(PS),* Global Instrumentation *(GS)* and finally Control Design *(CD)* is an evolutionary process as far model system formation and two typical forms of evolution are the s*tructural design evolution*, the *early-late design evolution* and the *interconnection topology evolution* [3]. Methodologies and tools developed for *Fixed Structure Systems*

(FES) cannot meet the challenges of the *SES* class and new developments on the level of concepts, modelling, analysis and synthesis methodologies are needed. The research is strongly influenced by the need to address life-cycle and re-design issues and such problems have a strong technological and economic dimension.

System of Systems: The notion of *"System of Systems"* (*SoS*) has emerged in many fields of applications from air traffic control to constellations of satellites, integrated operations of industrial systems in an extended enterprise to future combat systems. Such systems introduce a new systems paradigm with main characteristic the interaction of many independent, autonomous systems, frequently of large dimensions, which are brought together in order to satisfy a global goal and under certain rules of engagement. These complex multi-systems are very interdependent, but exhibit features well beyond the standard notion of system composition. They represent a synthesis of systems which themselves have a degree of autonomy, but this composition is subject to a central task and related rules frequently defined as "system plays" expressing the subjection of subsystems to a central task. This generalisation of the interconnection topology notion introduces special features and challenging problems, which are different than those presented by the design of traditional systems of the engineering domain. The distinguishing feature of this new form of complexity is [2]:

- The role of *"objects"*, or *"subsystems"* of the traditional system definition is taken by the notion of the *autonomous agent,* which may be characterised by some form of intelligence.
- The notion of *"interconnection topology*" of traditional systems is generalised to that of *"system*s play".
- Decision making and control may take the form of a game amongst the subsystems.

In this set up *emergen*ce takes a new form. There is a number of fundamental challenges, if the issue of design, or re-design *SoS* is to be addressed and the shaping of a new form of *System of Systems Engineering* methodology is to be addressed.

Addressing the issues of *SES* and *SoS* has important implications for the underpinning Control Theory and related Design methodologies. Control Theory and Design has developed considerably in the last forty years. However, the underlying assumption has always been that the system has been already designed and thus control has been viewed as the final stage of the design process on a system that has been formed. New paradigms have emerged which enlarge the area where Control is relevant and which challenge the *"fixed system structure assumption"*. These force us to reconsider some of the fundamentals (viewing Control as the final design stage on a formed system) and create the need for new developments where Control provides the concept and tools intervening in the overall design process, even at stages where the system is not fixed but may vary, may be under some evolution. Traditional Control has been capable to deal with uncertainty at the unit process level, but now has to develop to a new stage where it has to handle issues of structural, dynamic evolution of the system as well as control in the context of a "systems play". The paper provides an overview of the two areas, deals with issues of representation and introduces a research agenda for control into this new set up.

References

[1] N. KARCANIAS and A.G. HESSAMI, **2010.** "Complexity and the notion of System of Systems: Part (i): General Systems and Complexity; Part (ii) Defining the Notion of System of Systems". Proceedings of 2010 World Automation Congress International Symposium on Intelligent Automation and Control (ISIAC) 19 – 23 September 2010, Kobe Japan.

[2] N. KARCANIAS , **2013**. "Systems of Systems: A Control Theoretic View". Proceedings of IEEE SMC 2013 Conference (SMC2013:S01), October 13-16, Manchester.

[3] N. KARCANIAS, **2008.** ""Structure Evolving Systems and Control in Integrated Design" IFAC Annual Reviews in Control, Volume 32, Issue 2, December 2008,pp 161-182;

[4] N. KARCANIAS, **1995.** "Integrated Process Design: A Generic Control Theory/Design Based Framework", Computers in Industry, Vol. 26, pp 291-301.