“Systems Complexity: The Paradigm of System of Systems”

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★ BASIC OBSERVATION:

TRADITIONAL SYSTEMS ARE THE COMPOSITE SYSTEMS CHARACTERISED BY AN INTERCONNECTION TOPOLOGY

★ INTEGRATED SYSTEM OPERATIONS:

THE SYSTEM IS INTERCONNECTED AT THE INFORMATION & OPERATIONAL LEVEL WITH GENERAL RULES NOT EXPRESSING A TOPOLOGY

“SYSTEMS OF SYSTEMS”
Challenges in Engineering Design and Operations: Complex Systems Engineering & Complexity
COMPLEX DISTRIBUTED SYSTEMS

▲ Integration of Design / Operations of Technological Processes

▲ Power GENERATION & DISTRIBUTION Systems under Market De-regulation

▲ Networks of SYSTEMS: Control of Communication/ Traffic NETWORKS

▲ RAILWAY SYSTEMS AND OPERATIONS
EXAMPLES OF SYSTEMS OF SYSTEMS

What is a System of Systems?

Air traffic

Industrial Production

Freeways

Transportation SoS: Roads +GPS+ ONSTAR

Aircraft
Wireless Sensor Networks

- Environmental coverage
- Warning systems: fire detection//tsunami
- Defense applications: intruder detection, border surveillance
- Coverage: Search and rescue applications, toxic substance detection


web.engr.oregonstate.edu/~thinhq/re_sensor_network.html
Networked Mobile Robots

“Cooperative coverage using receding horizon control”, Ahmadzadeh et al., ECC’07, pp. 2466-2470

“Cooperative vision-based multi-vehicle dynamic coverage control for underwater applications”, Wang, Hussein, CCA’07, pp. 82-87

Actual Spatial/Temporal Robot Network Environment Description

Minimal robot communication constraints (line-of-sight, etc.)

Negligible on-robot energy constraints
INTEGRATED PROCESS OPERATIONS

Integrated System

Systems Classification:
Discrete, Continuous, Mixed (Batch)
INTEGRATED SYSTEMS

THE INTEGRATED VIEW
OF THE SYSTEM
LARGE SCALE INTEGRATED SYSTEM

SYSTEM FUNCTIONS
- Designer
- Specifications
- Risk
- Assurance
- Sustainability
- Reliability Indicators, Maintenance
- Human Resources, Management, Finance
- Quality (Products, Services) Indicators
- Systems Safety Indicators

SYSTEM OF SYSTEMS
- OPERATIONS LAYER
- CONTROL LAYER
- PHYSICAL LAYER

EMERGENT PROPERTIES
- Disturbances
- Disturbances
System of Systems: Empirical Characterisation

- **SoS**: A meta-system consisting of multiple autonomous embedded complex systems that can be diverse in:
  
  - Technology
  - Context
  - Operation
  - Geography
  - Conceptual frame

**Distinctions**

- An airplane is not SoS, but an airport is a SoS.
- A robot is not a SoS, but a robotic colony (a swarm) is a SoS

**CHALLENGES:** NEW ROLE OF INTERCONNECTION RULE + NOTION OF THE INTELLIGENT SYSTEM
THE DEFINITION OF THE SYSTEM

OBJECTS: SUBSYSTEMS, BASIC ELEMENTS

INTERCONNECTIONS: TOPOLOGY, RELATIONS

BOUNDARIES: EMBEDDING IN A LARGER SYSTEM

System Behaviour is different than the Aggregate of its parts

EMERGENT PROPERTIES
THE SYSTEM: TOPOLOGY, ENVIRONMENT & VARIABLES

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EMERGENT PROPERTIES
KALLICRATIDES NOTION OF THE SYSTEM

BASIC ELEMENTS OF THE DEFINITION

- BASIC ELEMENTS, OBJECTS
- RELATIONSHIPS BETWEEN OBJECTS
- PURPOSE OF THE SYSTEM, GOALS
- SYSTEM ENVIRONMENT

- The Lakonian, and Pythagorean Kallicratides:

("Περί οίκων εὐδαιµονίας") (Doric dialect in the Anthology of J. Stobaei, Economicos, 16, 485):

“Any system consists of contrary and dissimilar elements, which unite under one optimum and return to the common purpose”.

Examples:

- The system of dance in the singing societies
- The system of the crew in a ship
- The family (the household)
THE INTEGRATED INTELLIGENT SYSTEM

THE INTELLIGENT SYSTEM:
Signal Processing, Modelling, Estimation, Computations Decision Making and Control

AUTONOMOUS INTELLIGENT AGENT

INTEGRATED SYSTEM

SUPERVISORY ACTIVITIES
DECISION
CONTROLLER
IDENTIFICATION
MODELLING
PLANT
REALITY
ESTIMATION
SIGNAL PROCESSING

OPERATIONAL INSTRUCTIONS
OVERALL GOALS

INTERACTION WITH OTHER SYSTEMS

Input Influences
Output Influences
GENERALISING THE NOTION OF INTERCONNECTION TOPOLOGY

INTERCONNECTION TOPOLOGY FORMS

▲ FIXED INTERCONNECTION TOPOLOGY
   Traditional Composite Systems

▲ SYSTEM ORGANISATION
   Information and Control Structures, Operability

▲ EVOLVING INTERCONNECTION TOPOLOGIES
   Lifecycle Problems, Re-engineering

▲ AD HOC, STOCHASTIC INTERCONNECTIONS
   Communication Networks

▲ NOTION OF SYSTEM PLAY
   System of Systems
SYSTEM OF SYSTEMS

▲ **Composite Systems**: Composite notion
- Subsystems are not necessarily integrated.
- An interconnection topology is defined on the information Structures of the subsystems.

▲ **System of Systems**: Composite notion
- Subsystems are integrated systems acting as Independent intelligent agents.
  + The new notion of the “play” is introduced where the subsystems behave as “actors”.
  + A central Goal, frequently associated with a Game is defined where the subsystems participate as agents subject to the constraints of the play.

A Collection of independent systems interacting through an interconnection topology which are part of a central goal defining rule / game.
SYSTEM PLAY: A RULE, SCENARIO DEFINING THE OPERATIONAL RELATIONSHIPS BETWEEN THE INTEGRATED AND INTELLIGENT SUBSYSTEMS

APPROACHES FOR CHARACTERISATION OF THE SYSTEMS PLAY:

♦ CO-OPERATIVE CONTROL
♦ MARKET-ECONOMICS BASED COORDINATION TECHNIQUES
♦ POPULATION CONTROL METHODS
♦ COALITION GAMES
CLASSIFICATION OF SoS

SoS Classification Elements

▲ System Goal
▲ Systems Organisation
▲ System Play
RAILWAYS AS A SYSTEM OF SYSTEMS

CUSTOMER

EMERGENT SYSTEM PROPERTIES

THE RAILWAY SYSTEM

OPERATIONAL ISSUES

SYSTEM PROPERTIES

TECHNOLOGY

The Physical System
RAILWAYS AS A SYSTEM OF SYSTEMS

**EMERGENT PROPERTIES**
- Safety
- Reliability of Service
- Financial Viability, Cost
- Resilience of Operations, Sustainability
- Reduced Carbon Footprint

**OPERATIONAL ISSUES**
- Timetabling
- Mode of Operations
- Integration with Other Modes
- Pricing of services
- Ownership of the System & Services

**THE PHYSICAL SYSTEM**
- Infrastructure: Lines, Stations etc
- Signalling
- Rolling Stock
- Human Element

**TECHNOLOGY & DESIGN**

**SYSTEM PROPERTIES**
- Improved Track Quality
- Electric & Portable Fuel
- Onboard Energy Storage & Regeneration
- Optimising Energy Efficiency
- Maximising Capacity
- Quality of Ride etc

Customer

OPERATIONAL SYSTEM LEVEL

THE RAILWAY SYSTEM

PHYSICAL SYSTEM LEVEL
**Class: Multi-Modal Transportation System**

| Attributes | ▲ An aggregate of interrelated single mode transportation systems composite systems themselves;  
|            | ▲ The single modes are sustainable functioning systems on their own;  
|            | ▲ There’s mission dependency and criticality in the availability of each mode;  
|            | ▲ Constituent systems do not have specialised functions/roles. |

| Operations | ▲ Combination of diverse modes manifests desirable emergent properties such as lower cost, faster transport etc.  
|           | ▲ Emergence is not sustained with the loss of constituents  
|           | ▲ Emergence is weakened when constituents are at fault state  
|           | ▲ Has normal, degraded and failed operational states  
|           | ▲ In an operational context, there’s an additional emergency state |
# Emergent Properties

## Class: Emerging Property

| Attributes: | A physical or virtual feature arising from a whole system  
|            | Not present in constituents alone  
|            | May be physical or virtual  
|            | May not be discernable to the observer  
|            | Has varying degrees of strength currently viewed as weak and strong |

| Operations: | Is context dependent  
|             | Is lost when the whole is taken apart  
|             | Is weakened or lost when the whole is at fault (in constituent or topology)  
|             | Is mainly dependent on critical constituents |

## Challenge: Quantification, Measurement of Emergent Properties
PROBLEM: ORGANISATION OF INFORMATION AND CONTROL-DECISION MAKING STRUCTURES

CLASSIFICATION:

- HIERARCHICAL ORGANISATION
- HETEROARCHICAL ORGANISATION
- HOLONIC ORGANISATION
- OTHERS (BIONIC, GENETIC, FRACTAL, RANDOM)

HIERARCHICAL ORGANISATION
CONTROL ARCHITECTURE IN A HIERARCHICAL ORGANISATION

Integration of Operations in Technological Processes:

- HYBRID SYSTEMS
- “TOP DOWN”: GLOBAL CONTROLLABILITY
- “BOTTOM UP”
Complex system can arise and survive if they consist of stable, *autonomous* subsystems, each of them capable of surviving disturbances, but that are meanwhile able to *cooperate* to form a more complex, stable system *(Arthur Koestler)*

**HOLONIC ORGANIZATION**: Highly distributed organization of subsystems, where intelligence is distributed over the individual entities, subsystems, which are cooperative, intelligent, autonomous modules, called "holons." The subsystems work together in temporary hierarchies, the "holarchies" to achieve a global goal.

"*Holon"*: A combination from the Greek *holos*, meaning "whole" with the suffix -an, which, as in proton or neutron, suggesting a particle or part *(Arthur Koestler)*
EVOlUTIONARY SoS TRANSFORMATION ROADMAP

Integrated Composite Transformation

Collaborative SoS Transformation

Autonomous Communicating Transformation
**HOLONIC ORGANIZATION:** Preserves the stability of a hierarchy while providing the dynamic flexibility of a heterarchy and combines high performance with robustness against changes and disturbances.
COMPLEX SYSTEMS: SoS & SES THEORY CHALLENGES

▲ STRUCTURE EVOLVING SYSTEMS:
- Representation of forms of evolution
- Analysis & design of large scale integrated systems
- Integrating “top down” & “bottom-up” approaches
- Early-late design and system evolution
- Organisation of control & information structures, & decentralisation
- Design under uncertainty
- Redesign and system reconfiguration

▲ SYSTEM OF SYSTEMS:
- The representation problem
- From understanding to emergence & diagnostics
- Reduction and management of complexity by holonic organisation
- Game theory & design methodologies
- Systems integration: design, operational & business aspects
COMPLEX SYSTEMS CHALLENGES FOR TECHNOLOGICAL PROCESSES

▲ SYSTEMS Integration of Design, Operations & BUSINESS ASPECTS OF TECHNOLOGICAL PROCESSES
▲ SYSTEM OF SYSTEMS: FROM UNDERSTANDING TO DESIGN METHODOLOGIES
▲ ORGANISATION OF CONTROL & INFORMATION STRUCTURES, & DESIGN OF DECENTRALISATION
▲ REDUCTION AND MANAGEMENT OF COMPLEXITY BY HOLONIC ORGANISATION
▲ ANALYSIS & DESIGN OF LARGE SCALE INTEGRATED SYSTEMS: COMBINING THE “TOP DOWN” & THE “BOTTOM UP” APPROACHES
▲ DESIGN UNDER UNCERTAINTY
▲ OPERATIONAL FLEXIBILITY, REDESIGN AND SYSTEM RECONFIGURATION


