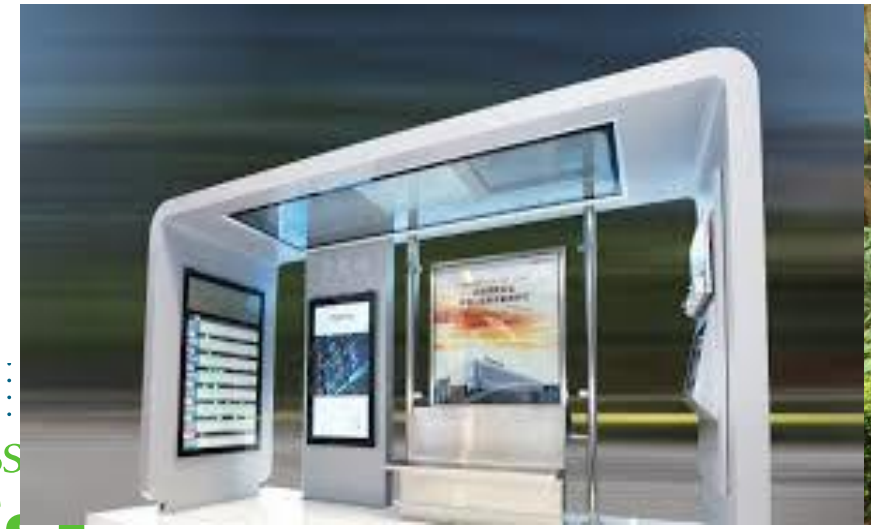
A Tool for Architecting Socio-Technical Problems: SoS Explorer

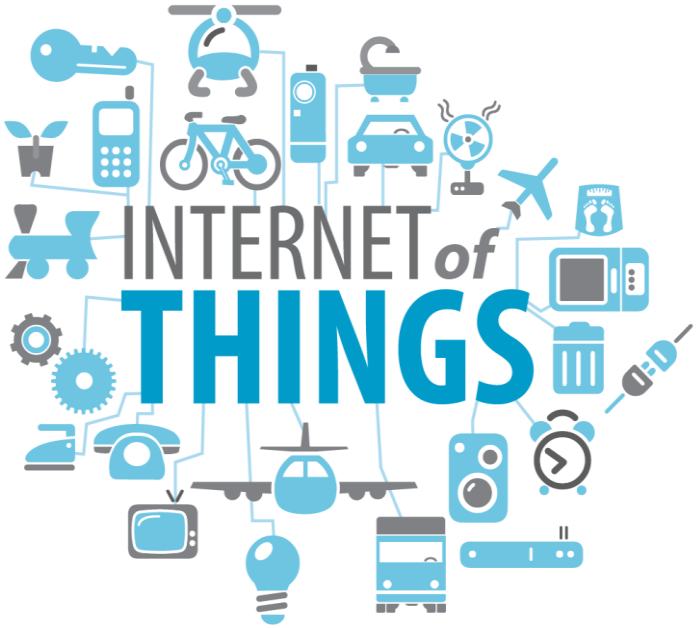
Cihan H. Dagli
Missouri University of Science and Technology

System of Systems

Changing Human Living Behaviors



System of Systems

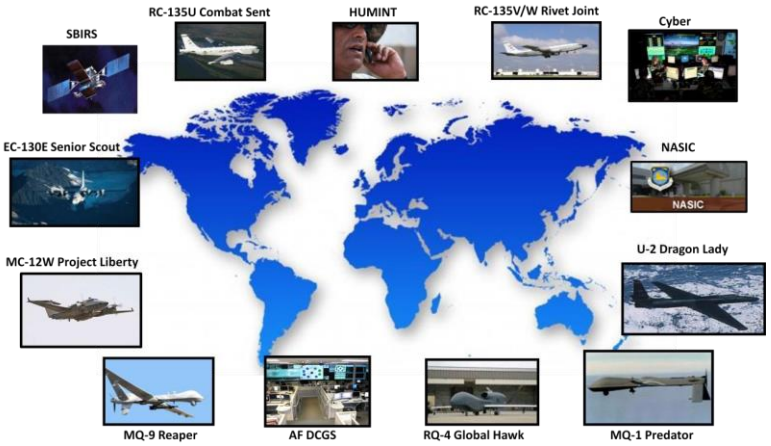


"The network of physical objects that contain embedded technology to communicate and interact with their internal states or the external environment."

MISSOURI S&T

System of Systems

Internet of Things for Defense



Internet of Things for Manufacturing

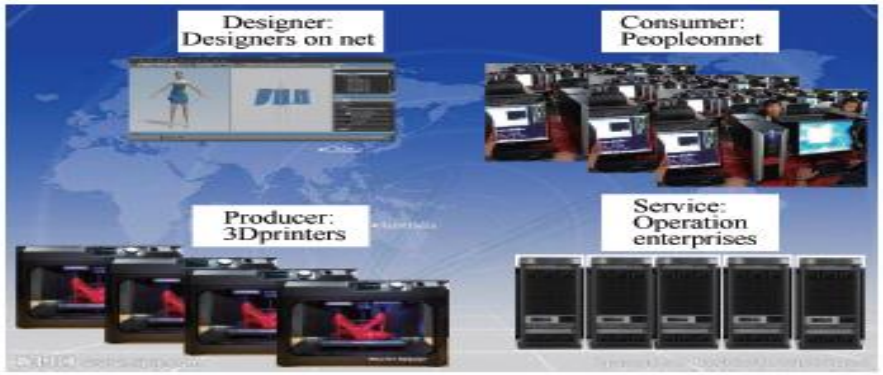
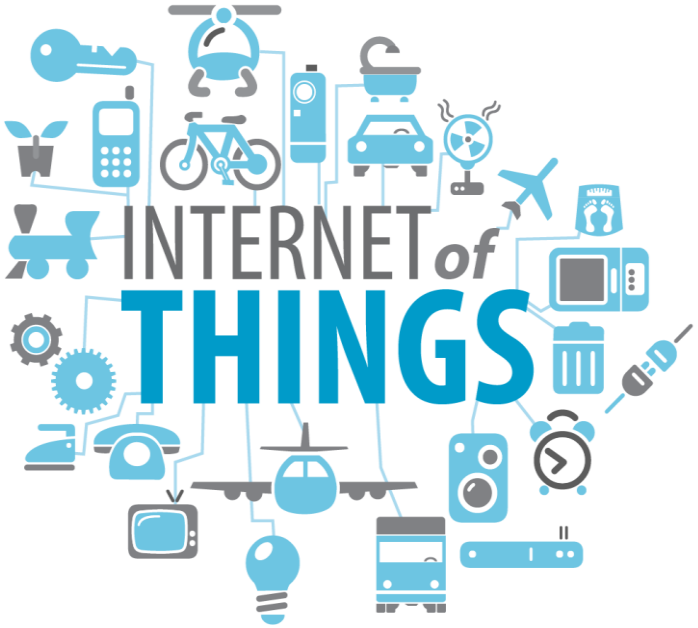


Fig. 4. Social manufacturing array with 3D printing centers.

From Mind to Products: Towards Social Manufacturing and Service Gang Xiong, et.al. IEEE/CAA JOURNAL OF AUTOMATICA SINICA, VOL. 5, NO. 1, JANUARY 2018

MISSOURI S&T

System of Systems



"This is a complex adaptive systems that can have emergent behavior and requires systems integration and engineering in their design and operation."

MISSOURI S&T

SYSTEM OF SYSTEMS

The integration of technology into society is a socio-technical problem. The solution to this type of problem results in a system of systems often called a cyber-physical system. These systems of systems are ubiquitous, ranging from transportation and healthcare to energy and defense. How well they are architected has a significant impact on sustainability and quality of life.

MISSOURI S&T

SOS ARCHITECTING

At its core, system of systems architecting is finding the set of systems and interfaces that best satisfy a set of given objectives while providing all of the the required capabilities. These objectives are the key performance measures of the architecture.

MISSOURI S&T

SOS CHALLENGES

Defining an optimal system of systems architecture poses significant difficulty as the problem presents:

- A high-dimensional solution space and trade space (difficult to search or visualize),
- Numerous objectives (causes Pareto breakdown and is difficult to optimize),
- Interactions that create emergent behaviors (difficult to predict).

MISSOURI S&T

APPROACH

1. Model each objective as a function of systems and interfaces. The systems are defined by characteristics, capabilities, and feasible interfaces.
2. Model architectural constraints in terms of systems, interfaces, and capabilities.
3. Use a many-objective optimization algorithm to find optimal architectures while maintaining constraints.
4. Provide solutions to the decision-maker in a manner that allows the decision-maker to modify solutions and to explore the trade-space.

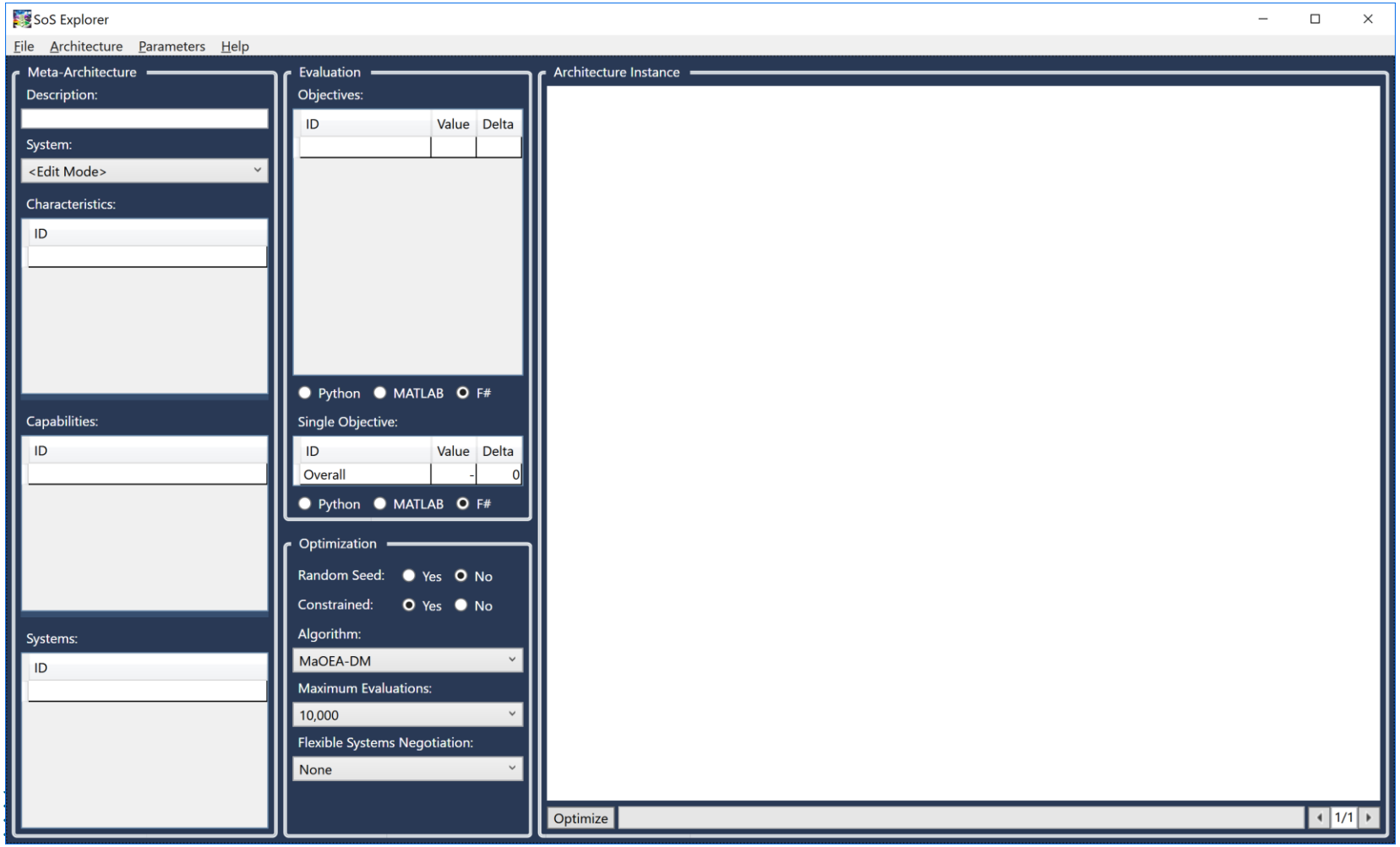
MISSOURI S&T

SOS EXPLORER

SoS Explorer is a tool developed by the Engineering Management and Systems Engineering department at Missouri University of Science and Technology. This tool incorporates the given approach, allowing modeling of objectives and constraints in three languages: MATLAB, Python, and F#. It utilizes evolutionary algorithms and supports both single- and many-objective optimization. It also provides an interactive GUI and real-time evaluation of solutions and deltas between solutions.

MISSOURI S&T

SOS EXPLORER GUI



MISSOURI S&T

EXAMPLE PROBLEM

To demonstrate this approach and the tool incorporating it, a toy problem is used. It is an intelligence, surveillance, and reconnaissance (ISR) problem involving twenty-two systems.

MISSOURI S&T

22-SYSTEM ISR PROBLEM

There are twenty two systems available supporting various ISR capabilities. The capabilities are:

- EO/IR
- SAR
- Exploit
- C2
- Comm

Each capability is required for a solution to be feasible.

There are four objectives:

- Performance
- Affordability
- Flexibility
- Robustness

The characteristics are:

- Interface cost
- Operations cost
- Performance
- Development time

MISSOURI S&T

SYSTEM CHARACTERISTICS

System	No. Avail.	I/F Dev Cost	Ops Cost	Perf	Dev Time
Fighter	3	0.2	10.0	10	1
Fighter SAR	3	0.7	15.0	10	1
RPA	4	0.4	2.0	15	1
U-2	1	0	15.0	3	0
DSP	1	1.0	0.1	8	1
JSTARS	1	0.1	18.0	40	1
Theater Exploit	2	2.0	10.0	10	1
ConUS	1	0.2	0.1	15	0
C^2	2	1.0	2.0	12	1
LOS	2	0.2	0.1	10	1
BLOS	2	0.5	3.0	10	1

MISSOURI S&T

SYSTEM CAPABILITIES

System	EO/IR	SAR	Exploit	C^2	Comm
Fighter	✓				✓
Fighter SAR		✓			✓
RPA	✓				✓
U-2	✓				
DSP	✓				
JSTARS		✓			✓
Theater Exploit			✓		✓
ConUS			✓		✓
C^2				✓	✓
LOS					✓
BLOS					✓

MISSOURI S&T

PERFORMANCE

The performance is the sum of the participating systems' individual performance which is augmented when there are interfaces to other participating systems. The formula is

$$\sum_{i=1}^{n} \left(\begin{cases} \text{Perf}_i, \text{if } S_i \\ 0, \text{otherwise} \end{cases} \right) \prod_{j=1}^{n} \begin{cases} 1+\delta, \text{if } S_j \wedge I_{ij} \\ 1, \text{otherwise} \end{cases}$$

Where $S_i, I_{ij}, \text{Perf}_i, \text{and } \delta$ represent the ith system's participation, the interface between the ith and jth systems, ith system's performance, and the performance boost provided by each implemented interface, respectively.

MISSOURI S&T

AFFORDABILITY

Affordability is related to the sum of the participating systems' individual operations costs along with the cost of implementing included interfaces. The formula is

$$-\sum_{i=1}^{n}\left(\begin{cases}\text{Ops Cost}_i, \text{if } S_i\\ 0, \text{otherwise}\end{cases}\right)\sum_{j=1}^{n}\begin{cases}\text{I/F Cost}_i, \text{if } I_{ij}\\ 0, \text{otherwise}\end{cases}$$

MISSOURI S&T

FLEXIBILITY

Flexibility is related to the surplus of capabilities in the SoS. The formula is

$$\sum_{i=1}^{n}\sum_{j=1}^{m}\begin{cases}1, \text{if } S_i \wedge \text{Cap}_{ij} \\ 0, \text{otherwise}\end{cases}$$

MISSOURI S&T

ROBUSTNESS

Robustness is related to loss of performance when the highest performing system is removed from the SoS. The formula is

$$-\max\left(\begin{cases} \text{Perf}_i, \text{if } S_i \\ 0, \text{otherwise} \end{cases}, \text{for } i = 1, 2, \dots, n\right)$$

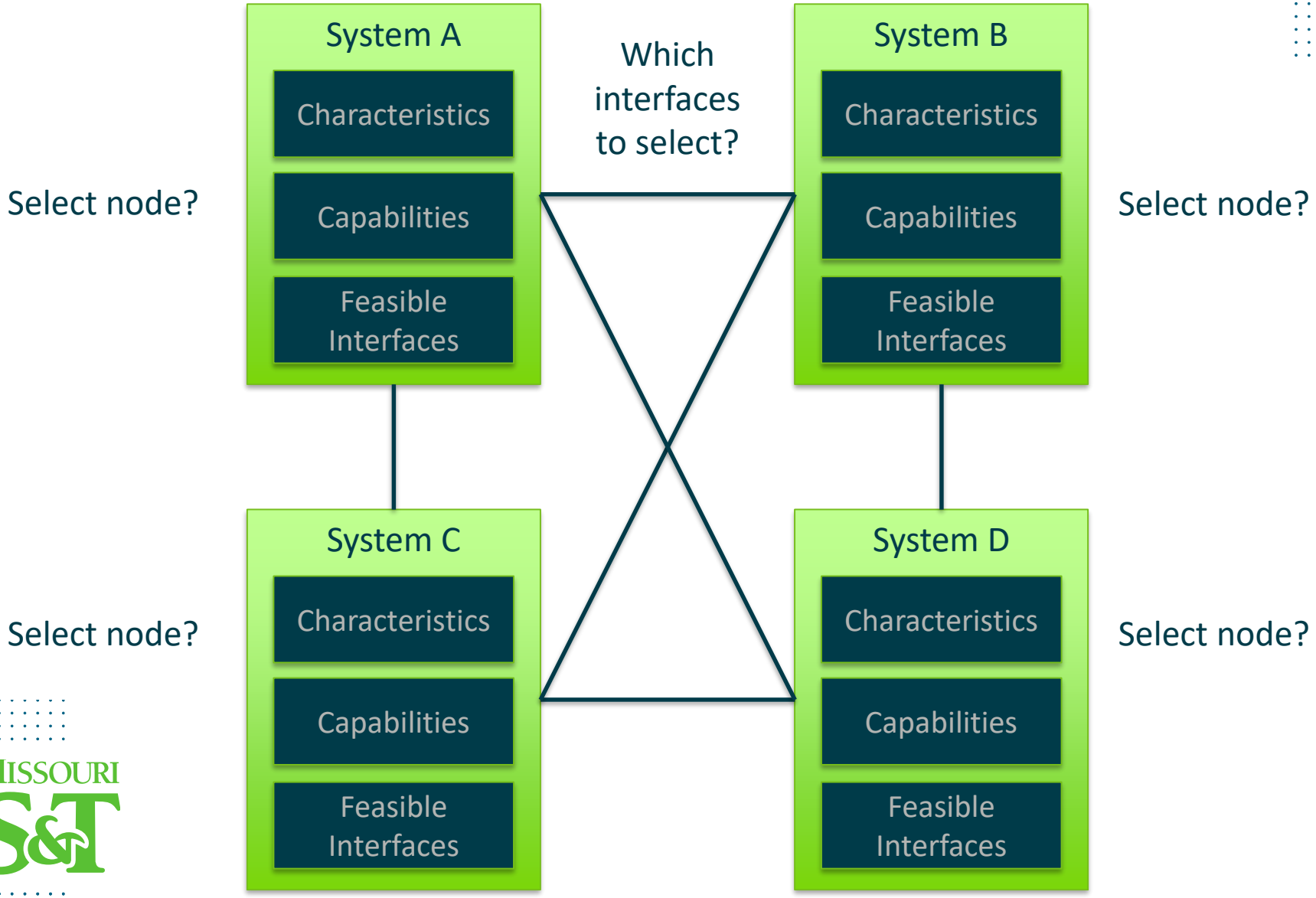
MISSOURI S&T

META-ARCHITECTURE

- In this approach, the architecture is modeled as a set of selected systems (nodes) and a set of selected interfaces connecting the systems (edges).
- The systems are modeled using the following:
  - Characteristics: Attributes characterizing performance (real values),
  - Capabilities: Attributes indicating presence of particular capabilities (Boolean values), and
  - Feasible interfaces: Attributes indicating the ability to interface with each of the other available systems (Boolean values).
- Interfaces may be either directed (unidirectional) or undirected (bidirectional).

MISSOURI S&T

META-ARCHITECTURE



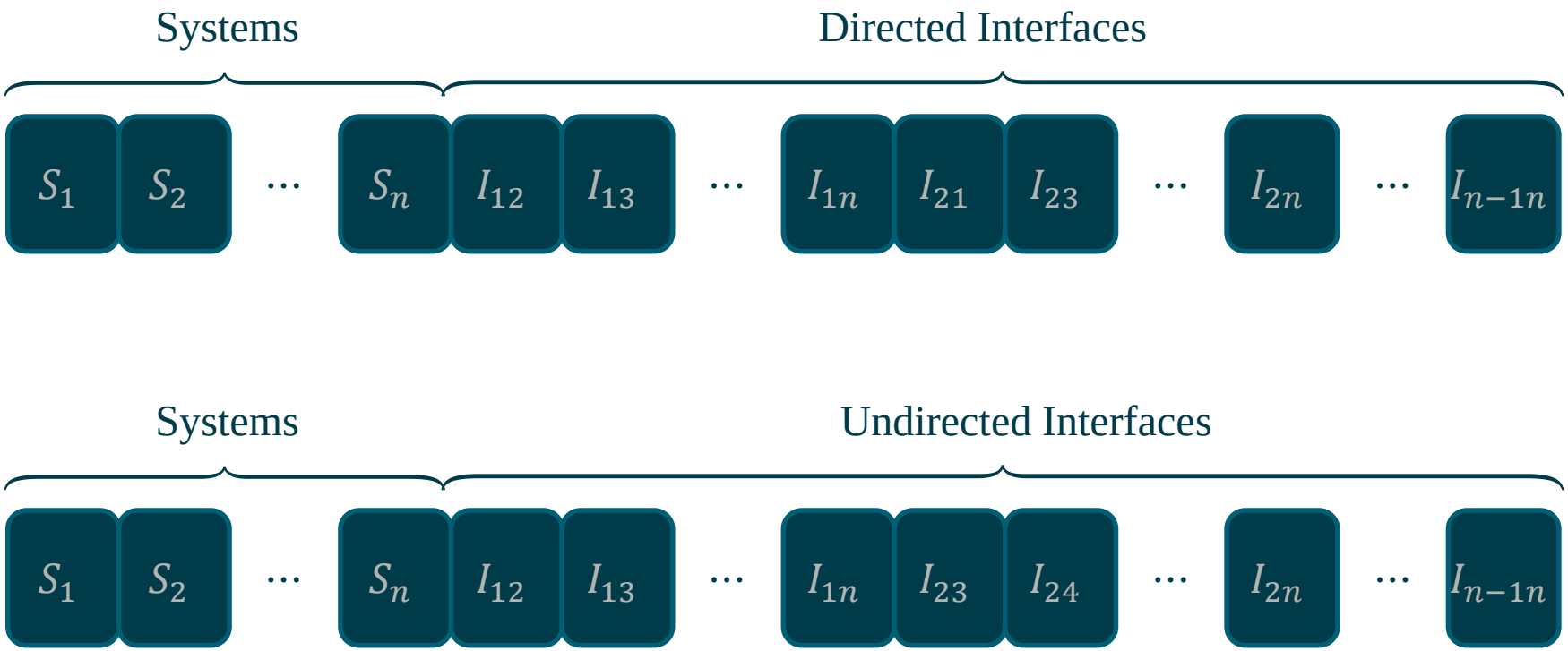
MISSOURI S&T

EVOLUTIONARY ALGORITHMS

- Because the objectives (KPMs) are commonly discontinuous, the optimization method employed must be non-gradient. The particular method chosen for this approach is that of evolutionary algorithms. They were chosen because:
  - Ease of representation of meta-architecture,
  - Wide acceptance,
  - Ability to enforce arbitrary constraints, and
  - Availability of many-objective evolutionary algorithms.
- Solutions are represented as chromosomes.

MISSOURI S&T

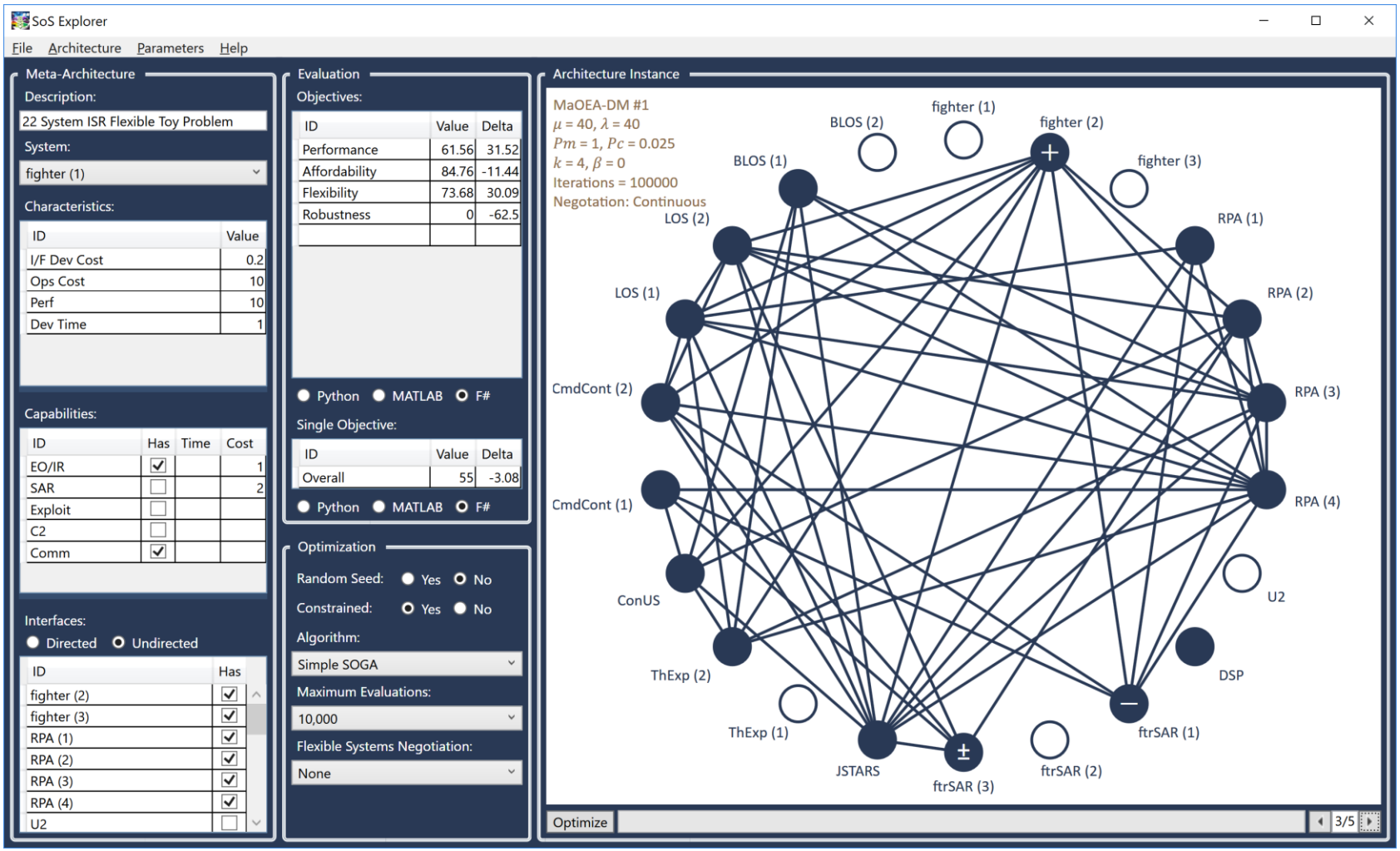
CHROMOSOME



MISSOURI S&T

(Show technology change)

RESULTS


SoS Explorer
File Architecture Parameters Help
Meta-Architecture
Description:
22 System ISR Flexible Toy Problem
System:
fighter (1)
Characteristics:
ID Value
I/F Dev Cost 0.2
Ops Cost 10
Perf 10
Dev Time 1
Capabilities:
ID Has Time Cost
EO/IR 1
SAR 2
Exploit
C2
Comm
Interfaces:
Directed Undirected
ID Has
fighter (2)
fighter (3)
RPA (1)
RPA (2)
RPA (3)
RPA (4)
U2
Evaluation
Objectives:
ID Value Delta
Performance 61.56 31.52
Affordability 84.76 -11.44
Flexibility 73.68 30.09
Robustness 0 -62.5
Python MATLAB F#
Single Objective:
ID Value Delta
Overall 55 -3.08
Python MATLAB F#
Optimization
Random Seed: Yes No
Constrained: Yes No
Algorithm:
Simple SOGA
Maximum Evaluations:
10,000
Flexible Systems Negotiation:
None
Architecture Instance
MaOEA-DM #1
μ = 40, λ = 40
Pm = 1, Pc = 0.025
k = 4, β = 0
Iterations = 100000
Negotation: Continuous
BLOS (2)
fighter (1)
fighter (2)
BLOS (1)
fighter (3)
LOS (2)
RPA (1)
LOS (1)
RPA (2)
CmdCont (2)
RPA (3)
CmdCont (1)
RPA (4)
ConUS
U2
ThExp (2)
DSP
ThExp (1)
ftrSAR (1)
JSTARS
ftrSAR (2)
ftrSAR (3)
Optimize
3/5

SOS EXPLORER

SoS Explorer is Missouri S&T's solution
http://emse.mst.edu/sos-explorer/

A novel optimization method called "MOEA-DM" tailored to the needs of cyber physical systems

Many-objective optimization

Use of clustering to cultivate a limited set of solutions of interest

Visualization of architectures
Interactive "what-if" experimentation

MISSOURI S&T

PUBLICATIONS

Abhijit Gosavi, Siddhartha Agarwal, Cihan H. Dagli: Predicting Response of Risk-Seeking Systems During Project Negotiations in a System of Systems. IEEE Systems Journal 11(3): 1557-1566 (2017)

Ruwen Qin, Cihan H Dagli and Nnaemeka Amaeshi. "A Contract Negotiation Model for Constituent Systems in the Acquisition of Acknowledged System of Systems" IEEE Transactions on Systems, Man, and Cybernetics: 47(11): 3050-3062 (2017)

Konur, Dinçer, Hadi Farhangi, and Cihan H. Dagli. "A multi-objective military system of systems architecting problem with inflexible and flexible systems: formulation and solution methods." OR Spectrum (2016): 1-40.

Dincer Konur and Cihan H Dagli "Military system of systems architecting with individual system contracts", Optimization Letters, December 2015, Volume 9, Issue 8, pp 1749-1767 http://link.springer.com/article/10.1007/s11590-014-0821-z

Kilicay-Ergin, N. and Dagli, C. (2015), "Incentive-Based Negotiation Model for System of Systems Acquisition". Syst. Engineering., 18: 310–321. doi:10.1002/sys.21305 http://onlinelibrary.wiley.com/doi/10.1002/sys.21305/full

Paulette Acheson, Cihan Dagli, and Nil Kilicay-Ergin, "Fuzzy Decision Analysis in Negotiation between the System of Systems Agent and the System Agent in an Agent-Based Model," in International Journal of Soft Computing and Software Engineering[JSCSE], Volume 3, No. 3, Pages 25-29, (www.jscse.com) ISSN 2251-7545, 2013.

MISSOURI S&T

PUBLICATIONS

Agarwal, Siddhartha, Cihan H. Dagli, and Louis E. Pape II. "Computational intelligence based complex adaptive system-of-system architecture evolution strategy." Complex Systems Design & Management. Springer International Publishing, 2016. 119-132.

Agarwal,S., Wang, R., & Dagli, C., (2015) FILA-SoS, Executable Architectures using Cuckoo Search Optimization coupled with OPM and CPN-A module: A new Meta-Architecture Model for FILA-SoS, in Complex Systems Design & Management (CSD&M) editor, Boulanger, Frédéric, Krob, Daniel, Morel, Gérard, Roussel, Jean-Claude, P 175-192 . Springer International Publishing.

Cihan H. Dagli and N. Kilicay-Ergin, "Chapter 4: System of Systems Architecting", in System of Systems Engineering, M. Jamshidi (editor), Wiley & Sons Inc., 2009, p. 77-101.

Gene Lesinski, Steven M Corns, Cihan H Dagli ” A fuzzy genetic algorithm approach to generate and assess meta-architectures for non-line of site fires battlefield capability” Evolutionary Computation (CEC), 2016 IEEE Congress on 24-29 July 2016. DOI: 10.1109/CEC.2016.7744085

Rahul Alaguvelu, David M Curry, Cihan H Dagli ” Fuzzy — Genetic algorithm approach to generate an optimal meta-architecture for a smart, safe & efficient city transportation system of systems “System of Systems Engineering Conference (SoSE), 2016 11th IEEE, June 12-16, 2016. DOI: 10.1109/SYSOSE.2016.7542935

MISSOURI S&T

PUBLICATIONS

George Muller, Cihan Dagli “Simulation for a coevolved system-of-systems meta-architecture” System of Systems Engineering Conference (SoSE), 2016 11th IEEE, June 12-16, 2016. DOI: 10.1109/SYSOSE.2016.7542931

Dagli, Cihan H. "Engineering Cyber Physical Systems: Machine Learning, Data Analytics and Smart Systems Architecting Preface." Procedia Computer Science 61 (2015): 8-9.

Agarwal, S., Pape, L.E., Dagli, C.H., Ergin, N.K., Enke, D., Gosavi, A., Qin, R., Konur, D., Wang, R. and Gottapu, R.D., 2015. Flexible and Intelligent Learning Architectures for SoS (FILA-SoS): Architectural Evolution in Systems-of-Systems. Procedia Computer Science, 44, pp.76-85.

Curry, David M., and Cihan H. Dagli. "A Computational Intelligence Approach to System-of-Systems Architecting Incorporating Multi-objective Optimization." Procedia Computer Science 44 (2015): 86-94.

MISSOURI S&T