SoSECIE Webinar

Welcome to the
2019 System of Systems Engineering Collaborators Information Exchange (SoSECIE)

We will start at 11AM Eastern Time

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NDIA System of Systems SE Committee

- **Mission**
  - To provide a forum where government, industry, and academia can share lessons learned, promote best practices, address issues, and advocate systems engineering for Systems of Systems (SoS)
  - To identify successful strategies for applying systems engineering principles to systems engineering of SoS
- **Operating Practices**
  - Face to face and virtual SoS Committee meetings are held in conjunction with NDIA SE Division meetings that occur in February, April, June, and August
  - SoS Track at NDIA 22nd Annual Systems Engineering Conference, Grand Hilton Tampa Downtown, Tampa, FL, October 21-24, 2019
    - Conference Info: http://www.ndia.org/events/2019/10/21/22nd-annual-systems-and-mission-engineering-conference

NDIA SE Division SoS Committee Industry Chairs:
Mr. Rick Poel, Boeing
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  - I will start with questions submitted online via the CHAT window in Skype.
  - I will then take questions via telephone; State your name, organization, and question clearly.
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2019 System of Systems Engineering Collaborators Information Exchange Webinars

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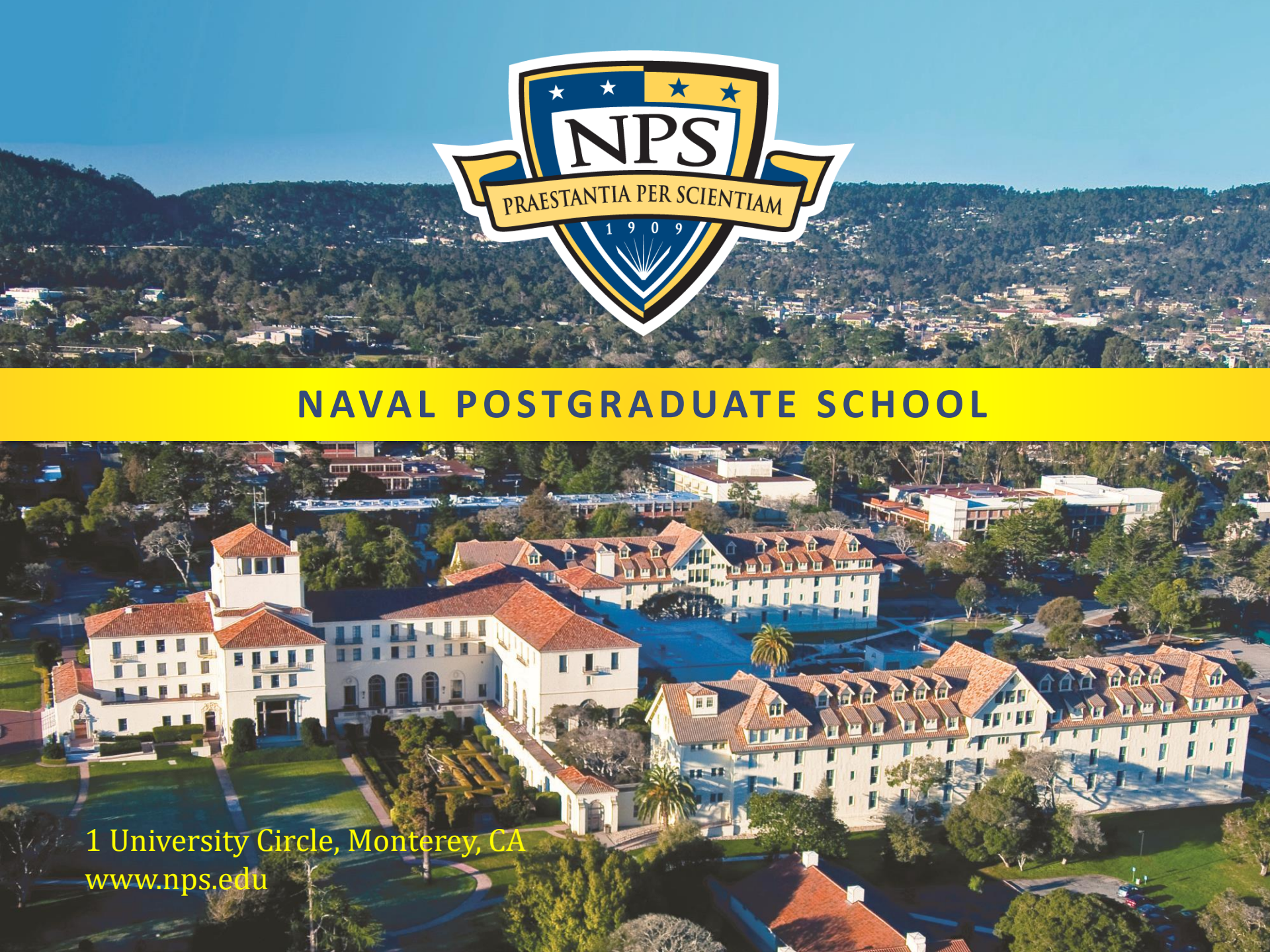
November 5, 2019
Irrational System Behavior in a System of Systems
Mr. Douglas L. Van Bossuyt, Mr. Bryan M. O'Halloran and Mr. Ryan M. Arlitt

November 19, 2019
Multi-Dimensional Classification of System-of-Systems
Dr. Bedir Tekinerdogen

December 3, 2019
Digital Twin Strategies for System of Systems
Mr. Michael Borth

December 17
TBD

January 14
Framework for Improving Complex System Performance
Mr. Chuck Keating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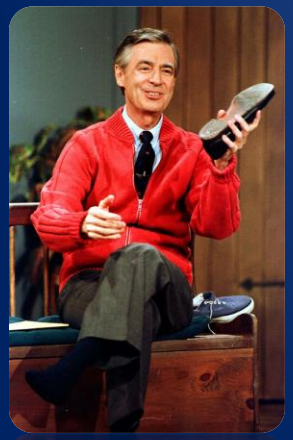
Recent Efforts to Help Systems be Good Neighbors in the Modern SoS Landscape: A System Architecture Approach



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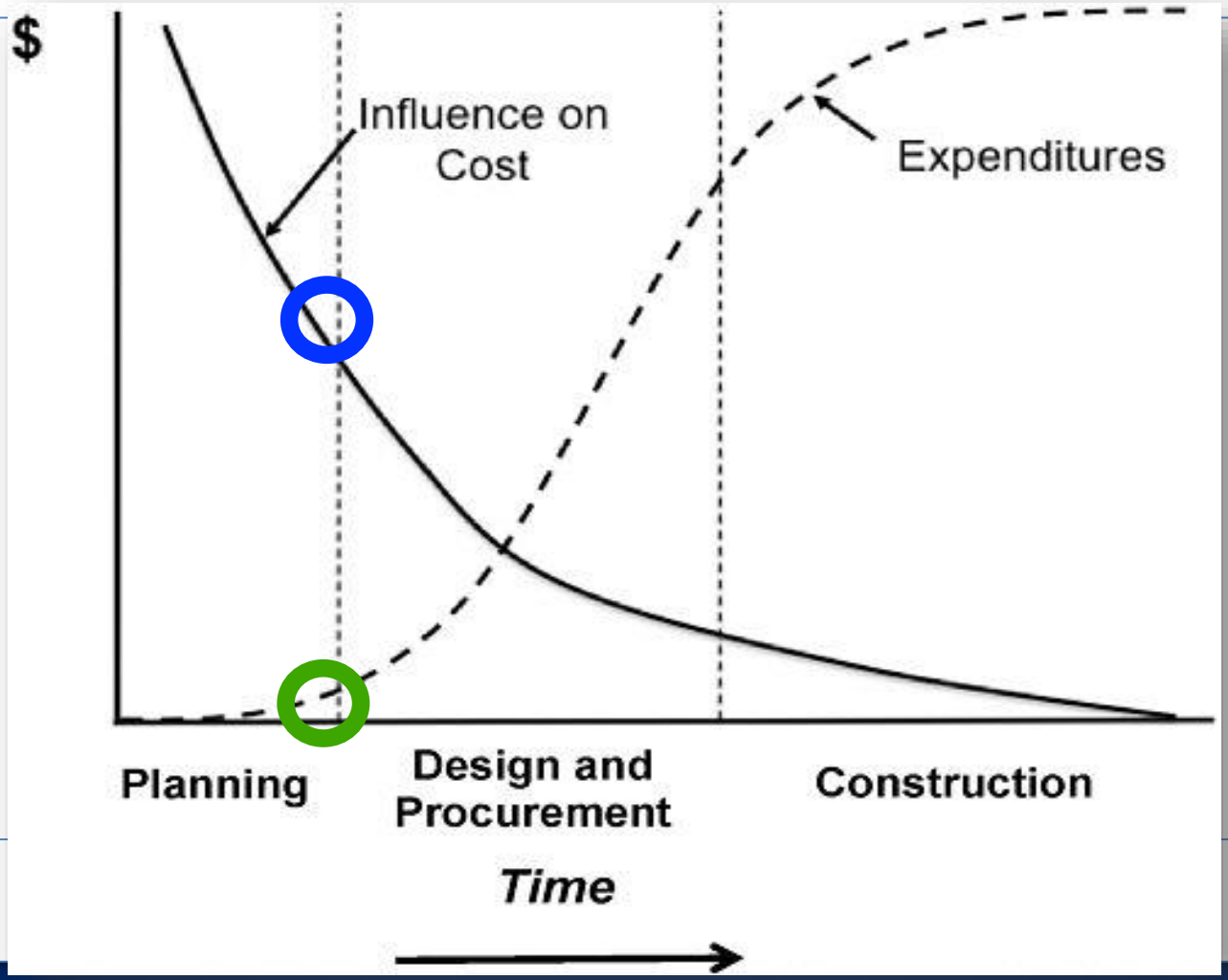
Overview

- Introduction
- Larger Picture of Research Effort
- Background and Related Work
- Methodology
- Case Study
- Discussion
- Future Work
- Conclusion

Introduction: Bigger Picture of Modern Design Approaches

- Have you ever heard?
  - Feel free to deliver the system late, or
  - We're hoping to relax the requirement of the next generation system
- Modern systems are developed on shorter schedules, smaller budgets…and the systems are being **expected to do more**
- Modern systems are highly connected and therefore have a high degree of failure potential
- Where's the opportunity to make big changes?

Introduction: Where we can have high impact on the system design process



Introduction: The issues we see

- Some spurious emissions are analyzed **after system architecture** process is complete
  - Makes it **more expensive** to identify and fix potential spurious emissions to help ensure systems are "good neighbors"
- Protecting a SoS member against incoming spurious emissions from other members is often addressed **after an incident**
  - We are good at our normal checklists, but not great at predicting things that have rarely been observed
- This presentation:
  - **Identify** and **address** potential spurious emissions during **functional** modeling of a member system
  - **Protect a member** system against spurious emissions from other systems during **functional** modeling

Larger Picture of Research Effort

- Heterogeneous SoS are the new normal
  - e.g., ships, planes, armored vehicles, autonomous systems, etc.
- Large constellation of contractors and OEMs building individual systems or subsystems
- Very messy integration
  - Surprises are **ALWAYS** found in the interactions

- Goal is to make flexible, extensible, reconfigurable SoS to adhere to new mission engineering thrust
  - Assemble SoS just **in time to complete missions**
  - Systems need to be "good neighbors" and be able to put up with systems that appear to be behaving irrationally

Background and Related Work

- SoS are becoming **more tightly coupled - connectivity**
  - Damage to one system can **propagate** throughout the SoS
  - One system can appear to behave irrationally and surprise other systems by unexpected/spurious emissions
- Resilience to faults in a SoS is becoming a more important topic to DoD and other industries (SoSE 2018)
- Most existing research is concerned with **identifying propagation** pathways, identifying/quantifying risk, etc. – *mostly applied to systems*
- Most existing research is only applicable once the functional architecture has been frozen and components have been selected
  - The progression of decisions during design **reduces the system's flexibility** to maneuver throughout the design space

Background and Related Work

- In our ongoing work we use:
  - Functional modeling (e.g., FBED taxonomy)
  - Failure analysis methods for inspiration and math
    - FMEA/FMECA, PRA, RBD, FFIP, UFFSR, etc…
- Focus is extending the FFIP family of methodologies
  - Method to examine how failures propagate through systems at the functional level

FFIP = Function Failure Identification and Propagation

- Also integration with PRA, RBD, or similar probabilistic-based and flow-modeling risk/reliability/failure analysis methods

Our Three Methods

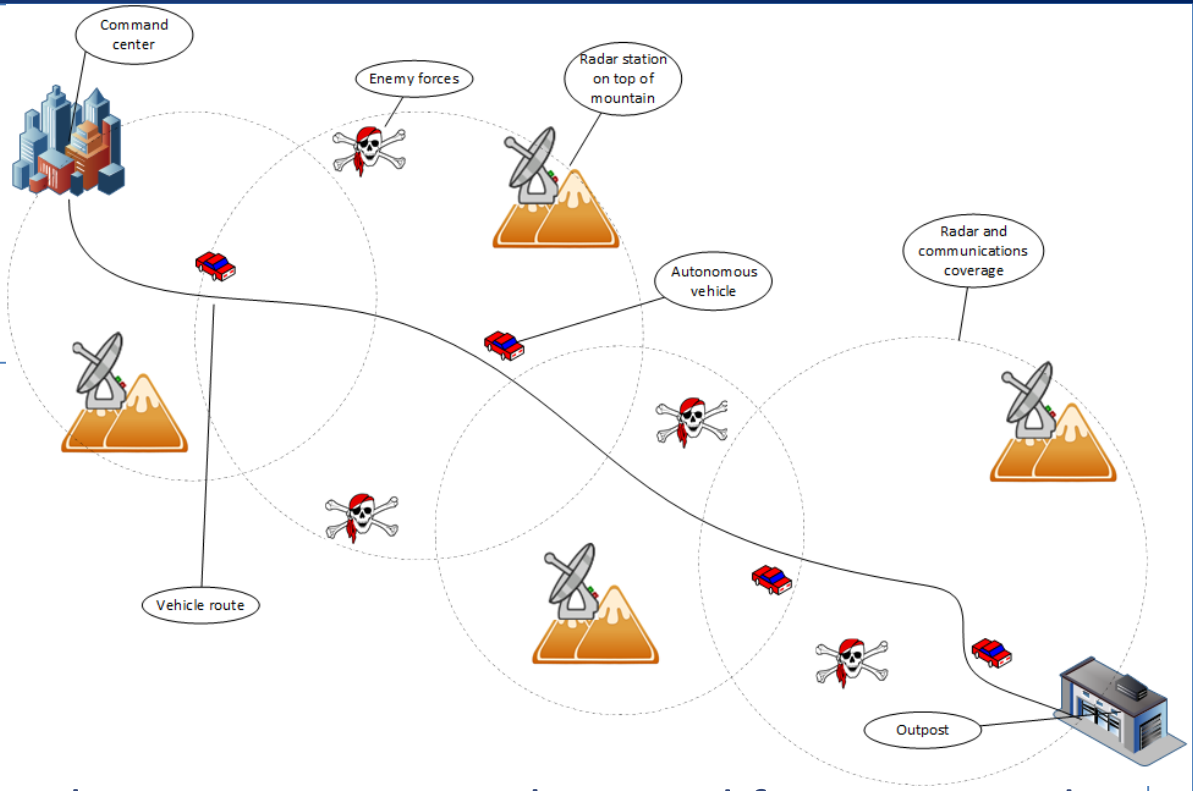
- Method 1: Prevent spurious emissions from emanating from a system
- Method 2: Prevent spurious emissions from entering a system
- Method 3: Develop SoS to be resilient to spurious emissions at the SoS level

- Methods 1 and 2 are published
- Method 3 is in process

Method 1: Prevent spurious emissions from emanating from a system

- Preparatory Step: Get all data and failure analysis together
- Step 1: Analysis of each function and what it conceivably could emit
- Step 2: Evaluate all potential flow paths through the system
- Step 3: Determine probabilities of spurious exiting flows
- Step 4: Analyze results
- Step 5: Identify spurious flow emission mitigation strategies
- Step 6: Determine what mitigation strategies to implement
- Step 7: Iterate and reanalyze

Case Study



- Autonomous vehicle entering service in an existing SoS
- SoS operates in a desert environment to carry materiel to FOB
- Requirement to operate with existing SoS members and future upgrades to the SoS over time
- UAV solution was down-selected from other potential autonomous delivery solutions due to mission requirements

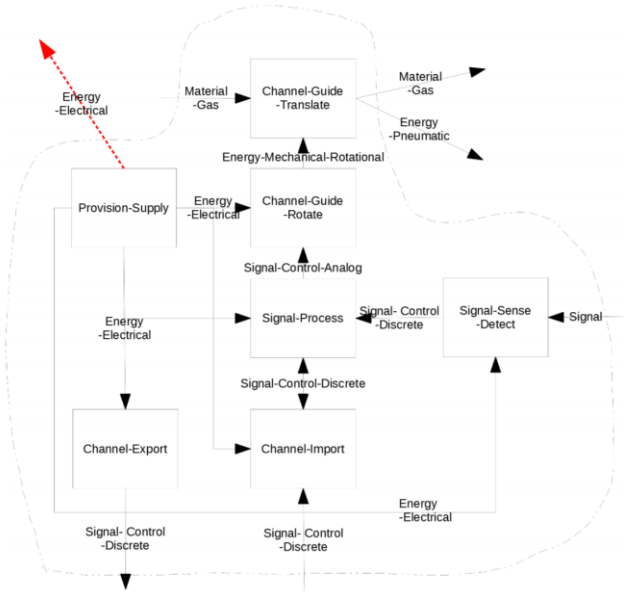
Req #	Requirement
#1	Carry 10kg 5km
#2	Complete round-trip transit with 99% success rate
#3	Communicate with ground control station at 1.5Mbit/sec TX/RX
⋮	⋮

Preparatory Step: Get all data and failure analysis together

- Prepare FFIP model of system
  - Including a function to component database
  - Including FSL implementation
- Prepare information needed for trade-off studies in Steps 6 and 7
  - Requirements info
  - Constraints
  - Other systems in SoS
  - Importance of system to SoS
  - Cost of failure of SoS
  - Known external initiating events

Function	Component Solution
Channel-Guide-Rotate	DC Electrical Motor
	AC Electrical Motor
	Pneumatic Motor
Provision-Supply	Lithium Polymer Battery
	Supercapacitor
	Lead Acid Battery
⋮	⋮

TABLE 2. Generic function to component repository for a UAV.



input : Nominal Flows, Failure Flows, System Operation Status
output: Nominal Flows, Failure Flows
Let P1 = Sample from a Uniform(0,1) Random Distribution
Let P2 = Sample from a Uniform(0,1) Random Distribution

while *System Operation Status == True* **do**
  if *Energy-Electrical Failure Import Flow == True* **then**
    if $0.2 < P1 < 0.4$ **then**
      Export Failure Flow = Energy-Thermal, Material-Mixture-Gas/Solid Export
      Nominal Flow = False
    end
    else if $P1 \leq 0.2$) **then**
      Export Failure Flow = Energy-Electrical
      Export Nominal Flow = False
    end
    else
      if *Electrical-Energy Nominal Import == True* **then**
        Export Failure Flow = False Export Nominal Flow = Energy-Electrical
  if *Material-Solid-Object Failure Import Flow == True* **then**
    if $P2 < 0.2$ **then**
      Export Failure Flow = Energy-Thermal, Material-Mixture-Gas/Solid Export
      Nominal Flow = False
    end
    else
      Export Failure Flow = False
      if *Electrical Energy Nominal Import == True* **then**
        Export Nominal Flow = Energy-Electrical
      else
        Export Nominal Flow = False
      end
  if *Failure Import Flow == False* **then**
    if *Electrical-Energy Nominal Import == True* **then**
      Export Nominal Flow = Energy-Electrical
    else
      Export Nominal Flow = False
    end
  else
    Export Nominal Flow = False
  end
end

Algorithm 1: Failure flow information for a generic Provision-Supply function.

Prep Step (con't)

- Example of consequences of SoS failure

Failure Flow Exports from System of Interest that Lead to Initiating Events for Other Systems in SoS	Consequence	C_e
Energy-Electrical	Static-electric discharges during dust storms caused by UAV rotors or propellers can short out onboard electronics of nearby vehicles leading to loss of both UAVs and UGVs	$5M
Material-Solid-Particulate	Large particulate from crashed UAVs can clog air vents and cause over-heating of UGVs leading to disabled systems	$1M
Material-Control-Analog	Interference with radio transceivers causes UAVs to automatically land regardless of terrain or of potential adversary presence	$2M
⋮	⋮	⋮

TABLE 3. Consequence data for an mixed UAV and UGV SoS where consequence the cost distribution function C_e for the impact of the system on the SoS. In this example, each C_e is a point distribution.

Step 1: Analysis of each function and what it conceivably could emit

- Take a very broad view of what each function might conceivably be able to emit
  - For example, if you hit anything with enough energy, it will do something very unexpected compared to nominal operation
- We suggest working backwards from FBED flow set to try and disprove that each flow can be emitted from a function

Step 1: Con't

- Table shows disproving that each flow can conceivably be emitted from a function

TABLE 4. Generic example of examining potential failure flows and determining if they can occur using the FBED flow set for a Channel-Guide-Rotate function in a UAV system. Failure flows generated by specific component solutions are indicated on the right hand side of the table.

Failure Flow Imports			→	Failure Flow Exports			
Primary	**Secondary**	**Tertiary**	→	**Primary**	**Secondary**	**Tertiary**	**Component Solution(s) to Function**
				Material	~~Human~~		
Energy	Mechanical	Translational	→		Gas		DC Motor
Energy	Electrical		→		Liquid		AC Motor
Energy	Mechanical	Translational	→		Solid	Object	DC Motor, AC Motor
Energy	Mechanical	Translational	→			Particulate	DC Motor, AC Motor, Pneumatic Motor
						~~Composite~~	
					~~Plasma~~		
					~~Mixture~~	~~Gas-gas~~	
						~~Liquid-liquid~~	
						~~Solid-solid~~	
						~~Solid-Liquid~~	
						~~Liquid-Gas~~	
						~~Solid-Gas~~	
						~~Solid-Liquid-Gas~~	
						~~Colloidal~~	
				Signal	Status	~~Auditory~~	
						~~Olfactory~~	
						~~Tactile~~	
						~~Taste~~	
Energy	Mechanical	Pneumatic	→			Visual	Pneumatic Motor
Energy	Electrical		→		Control	Analog	AC Motor
Energy	Electromagnetic	Solar	→	"	"	"	AC Motor
						~~Discrete~~	
				Energy	~~Human~~		
					~~Acoustic~~		
					~~Biological~~		
					~~Chemical~~		
					~~Electrical~~		
Energy	Electrical		→		Electromagnetic	Optical	DC Motor
						~~Solar~~	
					~~Hydraulic~~		
					~~Magnetic~~		
					~~Mechanical~~	~~Rotational~~	
						~~Translational~~	
						~~Pneumatic~~	
					~~Radioactive/Nuclear~~		
Energy	Radioactive/Nuclear		→		Thermal		AC Motor, DC Motor, Pneumatic Motor

Step 2: Evaluate all potential flow paths through the system

- Conduct new FFIP/FSL/UFFSR analysis with all potential failure flows from each function
  - Just because you can't postulate how such a flow might initiate under normal system operation doesn't mean it won't

Flow Path #	Failure Flow Path
#1	Energy-Electrical → Provision-Supply → Energy-Electrical → Channel-Export → Signal-Control-Discrete
#2	Material-Mixture-Gas/Solid → Channel-Guide-Translate → Material-Solid
#3	Provision-Supply → Energy-Electrical → Channel-Guide-Rotate → Energy-Thermal
⋮	⋮

TABLE 5. Example failure flow paths of a generic UAV system that exit the system boundary.

Step 3: Determine probabilities of spurious exiting flows

- Aggregate FFIP cut-set results for each spurious flow that can leave a system
  - Many cut-sets with many different initiating events may contribute to one spurious flow emission

Failure Flow System Emission	PO_e
Energy, Mechanical, Translational	2.2E-4/year
Material, Gas	4.3E-3/year
Signal, Status, Visual	5.6E-3/year
Material, Solid, Particulate	1.9E-2/year
Material, Liquid	8.3E-3/year
⋮	⋮

TABLE 6. Probability of occurrence of a representative set of failure flow system emissions for a generic UAV system.

Step 4: Analyze results

Priority	Failure Flow System Emission	P_e
#1	Signal,Status,Visual	2.1E-4/year
#2	Material,Liquid	8.3E-5/year
#3	Material,Solid,Particulate	1.9E-5/year
⋮	⋮	⋮

TABLE 7. Priority ranking based on probability of adversely impacting other systems in the SOS with a failure flow leaving the system boundary as a spurious emission (P_e). Note that P_e is not the same as the probability of occurrence in Table 6 – P_e is the probability of negative consequences on other systems in the SoS while probability of occurrence is of the failure flow being emitted from the system.

- We advocate you analyze as follows:
  - Examine other current and predicted future SoS members that could be impacted by spurious emissions
    - Many ways to understand this such as:
      - Dollar amount of loss
      - Mission success
      - Availability of SoS
  - We suggest developing Emission Priority Distribution (EPD) as a metric to make a comparison between spurious emissions to understand which is worse

Failure Flow System Emission	P_e	C_e	EPD
Energy-Mechanical-Translational	5.2E-4/year	$5M	$2600/yr
Material-Solid-Particulate	1.9E-5/year	$1M	$19/year
Material-Control-Analog	2.6E-4/year	$2M	$520/year
⋮	⋮	⋮	⋮

TABLE 8. EPD Analysis of a generic UAV system that is part of a mixed UAV and UGV SoS. P_e comes from Table 6 and C_e is from Table 3.

$$EPD_e = P_e * C_e$$

Step 5: Identify spurious flow emission mitigation strategies

- We're trying to avoid the "tragedy of the commons" by not being selfish systems engineers
  - Attempt to mitigate spurious emissions before exiting system
    - FCC and CARB require this for EMF and tailpipe emissions
- Emission priority distribution reduction:
- Mitigation probability distribution:
- These metrics help us to understand which mitigation strategies are preferred based on which spurious emissions do the most harm on a cost basis

$$\mathbf{EPD_{Reduced_{(e,m)}}} = P_{Me_{(e,m)}} * C_{e_{(e,m)}}$$

$$\mathbf{MPD} = \overrightarrow{EPD}^{\mathsf{T}} * \mathbf{EPD_{Reduced}} + \mathbf{M_C}$$

$$\mathbf{EPD_{Reduced_{e,m}}} = \begin{bmatrix} EPD_{Post-Mitigation_{1,1}} & EPD_{Post-Mitigation_{1,2}} & 0 \\ 0 & 0 & EPD_{Post-Mitigation_{2,3}} \\ 0 & EPD_{Post-Mitigation_{3,2}} & 0 \\ EPD_{Post-Mitigation_{4,1}} & 0 & EPD_{Post-Mitigation_{4,3}} \\ \vdots & \vdots & \vdots \end{bmatrix}$$

Step 6: Determine what mitigation strategies to implement

- We propose mitigation rank priority to make down-selects on what spurious emissions to mitigate in cost constrained environments
- Can use this approach to conduct trade-off studies on which mitigation strategies deliver biggest “bang for the buck”

$$MRP_m = rank(max(MPD_m)) + rank(mean(MPD_m)) + rank(std(MPD_m))$$

Step 7: Iterate and reanalyze

- After deciding what spurious flow mitigations to include in a system, reanalysis is key
  - New spurious emissions may be generated by mitigation strategies
  - Continue to iterate and reanalyze until you are happy with remaining spurious emissions

Failure Flow System Emission	Mitigation Strategy Function(s)	Physical Solution(s)	P_{Me}	New Failure Flow(s)	NFFLS?	P_{Mf}	M_C
Energy,Mechanical, Translational	Control Magnitude,Stop,Inhibit	Shielding to prevent rotor strikes	4.7E-5/year	Material,Solid,Object	Yes	3.5E-3/year	$300k
Signal,Status,Visual	Signal,Process	Redundant control system to verify visual control signals before sending	4.2E-5/year	No	No	0	$1M
Material,Liquid	Provision,Store, Contain	Catchment subsystem to retain any liquid generated by failed battery cells	5.2E-5/year	No	No	0	$500k
”	Channel,Export	Long hose to direct liquid to ground	6.2E-5/year	Material,Mixture,Liquid-Solid	Yes	3.1E-5/year	$250k
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

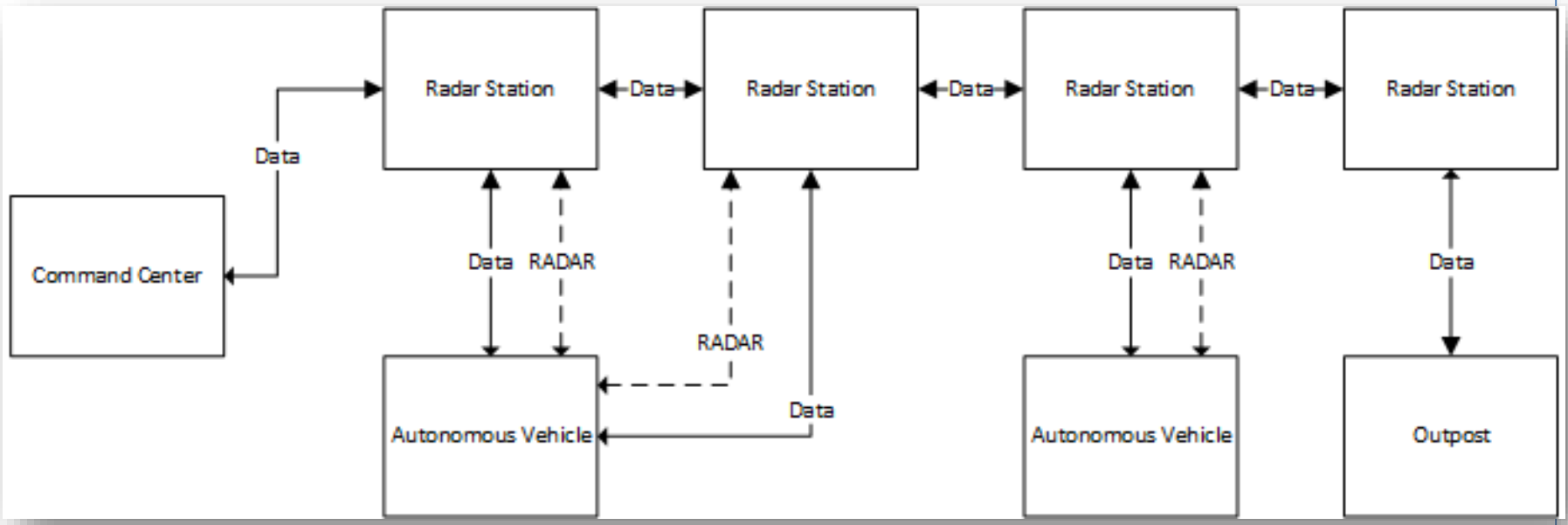
TABLE 9. Generic mitigation strategies for a UAV. P_{Me} is the probability of a mitigated system failure flow emission still occurring. NFFLS represents if a new failure flow may leave the system from the mitigation strategy function. P_{Mf} is the probability distribution function of a new failure flow leaving the system. M_C is the mitigation cost distribution function.

Method 2: Prevent spurious emissions from entering a system

- Step 1: Model the system of systems and the constituent systems
- Step 2: Identify “irrationality initiators”
- Step 3: Analyze the impact of “irrationality initiators” on systems within the SoS
- Step 4: Interpret the results

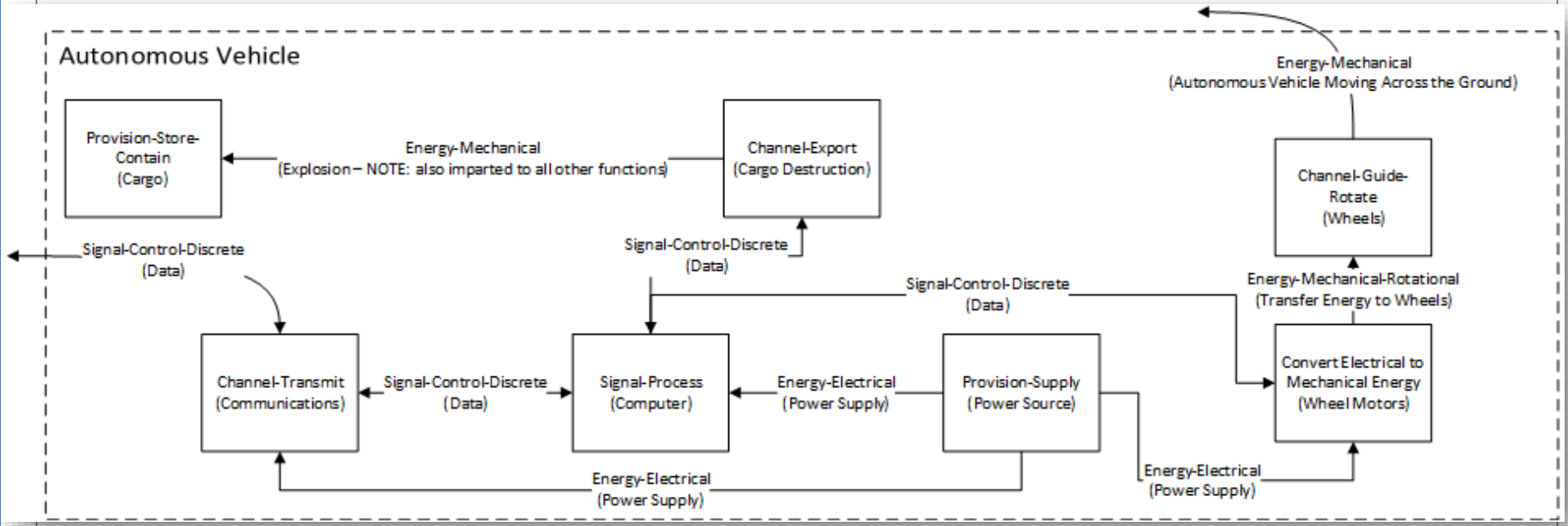
Step 1 Part 1: Functional block diagram of the SoS

- Establishes the potential basic failure propagation pathways



Step 1 Part 2: Functional block diagram of the system of interest

- Understand the core functions and flows of the system

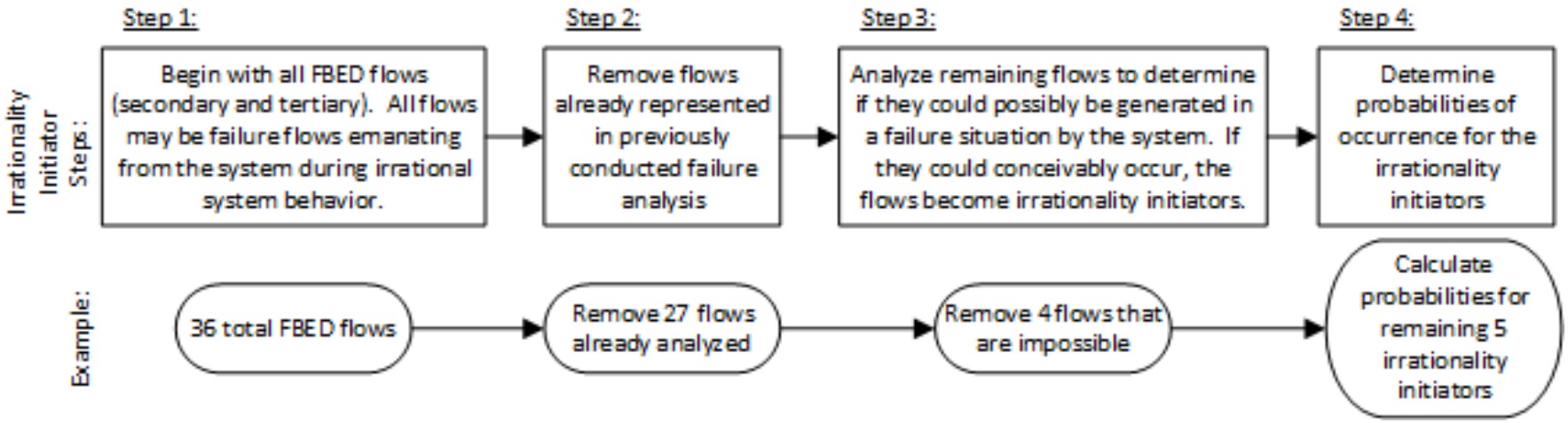


Step 2: Identify potential irrational system behaviors (irrationality initiators)

- Irrationality initiators become new initiating events for individual systems
- Big idea: We are searching for potential actions that other systems within the SoS can take that will initiate failure events in the system of interest
  - We are looking for **irrational events** that we never would believe possible as systems engineers
  - But we are System of Systems engineers!

Sub-Steps to develop the irrational initiators

- 1: Begin with ALL secondary and tertiary flows from functional taxonomy
- 2: Remove flows already represented in previous failure analysis (do not need to analyze them a second time)



Sub-Steps to develop the irrational initiators

- 3: Analyze remaining functional flows to determine if there is any possible way that they could be emitted by the other systems
  - "Wacky Ideas" part of your brain needs to be involved – the outlandish and bizarre often have a way of happening to real systems in the field
  - A failure initiator for one system might be another system's normal emissions
  - Remove those that are absolutely impossible
- 4: Develop probabilities of occurrence of potential remaining functional flows that could be emitted from other systems

Sub-Steps to develop the irrational initiators

- From the Functional Basis for Engineering Design (FBED)
- Other functional taxonomies can also be used
- Up to the practitioner to select appropriate taxonomy
- We like FBED for being abstract

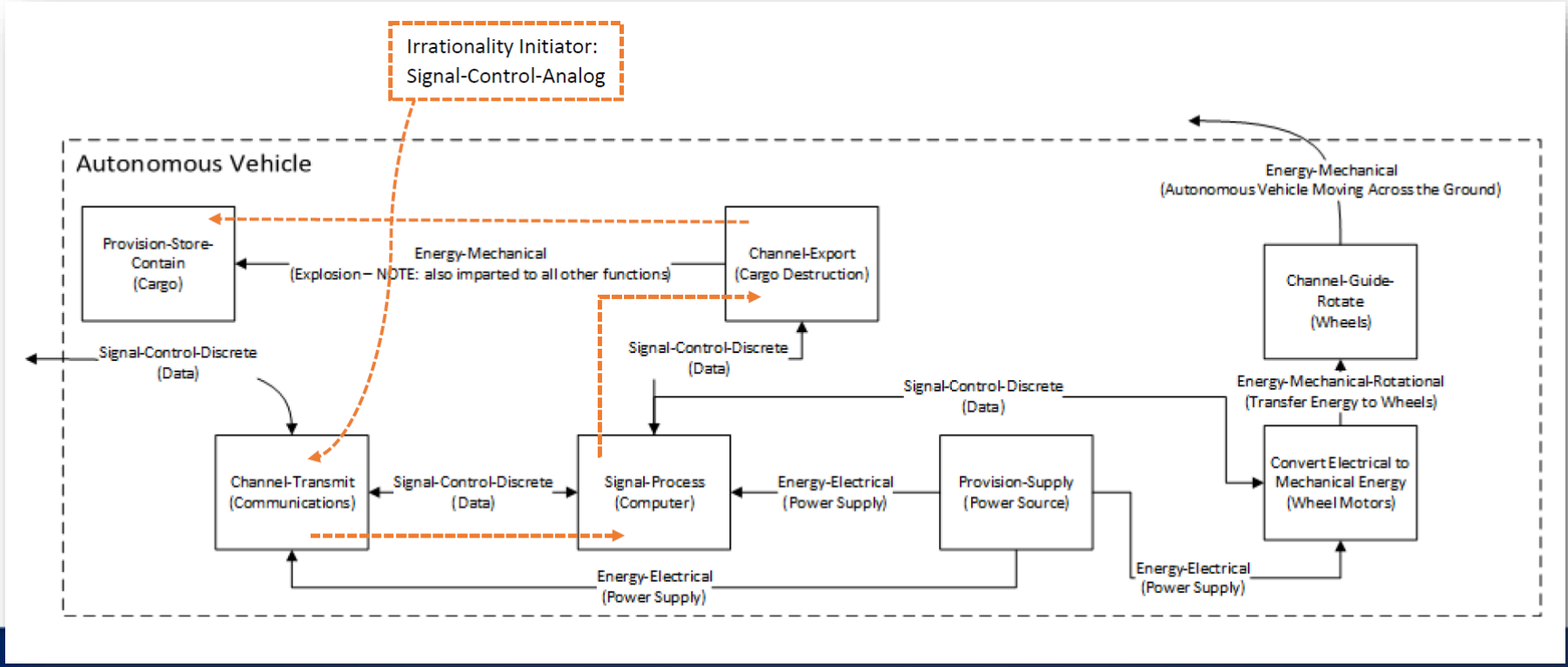
Primary	Secondary	Tertiary	Probability
Material	~~Human~~		
	~~Gas~~		
	~~Liquid~~		
	Solid	Object	1E-2/day
		~~Particulate~~	
		~~Composite~~	
	~~Plasma~~		
	~~Mixture~~	~~Gas-gas~~	
		~~Liquid-liquid~~	
		~~Solid-solid~~	
		~~Solid-Liquid~~	
		~~Liquid-Gas~~	
		~~Solid-Gas~~	
		~~Solid-Liquid-Gas~~	
		~~Colloidal~~	
Signal	~~Status~~	~~Auditory~~	
		~~Olfactory~~	
		~~Tactile~~	
		~~Taste~~	
		~~Visual~~	
	Control	Analog	1.7E-3/day
		~~Discrete~~	
Energy	~~Human~~		
	~~Acoustic~~		
	~~Biological~~		
	~~Chemical~~		
	~~Electrical~~		
	Electromagnetic	~~Optical~~	
		Solar	8E-8/day
	~~Hydraulic~~		
	~~Magnetic~~		
	~~Mechanical~~	~~Rotational~~	
		~~Translational~~	
	~~Pneumatic~~		
	~~Radioactive/Nuclear~~		
	~~Thermal~~		

Step 3: Analyze potential irrationality initiators for their impact on system of interest

- We recommend using the Function Failure Identification and Propagation (FFIP) modeling method
- Look for how a flow interacts with a system. Some flows will have no impact on a system while other flows can be disastrous.
- Look both for flows entering through nominal flow paths and flows entering through ways that are unexpected
  - We recommend using the Uncoupled Failure Flow State Reasoner (UFFSR) method to identify non-nominal flows

Example of an irrationality initiator causing the autonomous vehicle to fail

- Analog signal damages digital transmitter
  - Causes power surge in other systems, destroying vehicle via self destruct system



Step 4: Look at the results of the risk analysis (using FFIP)

- Output is similar to cut-sets in Probabilistic Risk Assessment (PRA) tools
- Shows the biggest risks to the smallest risks in rank order

Failure Propagation Pathway	Probability
Signal-Control-Discrete, Channel-Transmit, Signal-Process, Convert Electrical Energy to Mechanical Energy, Channel-Guide-Rotate	1.2E-3/day
Provision-Supply, Signal-Process, Signal-Control-Discrete, Channel-Export, Provision-Store-Contain	2.7E-3/day
Signal-Control-Discrete, Channel-Transmit, Signal-Process, Channel-Export, Provision-Store-Contain	3.7E-4/day
Energy-Mechanical, Channel-Guide-Rotate, Convert Electrical to Mechanical Energy, Provision-Supply, Signal-Process, Channel-Export, Provision-Store-Contain	1.4E-5/day
Signal-Process, Channel-Transmit, Provision-Supply, Convert Electrical to Mechanical Energy, Channel-Guide-Rotate	5.4E-5/day

- Now we can work on redesigning systems within SoS

Method 3: Develop SoS to be resilient to spurious emissions at the SoS level

- Work in progress
- Major considerations:
  - How do we conduct this analysis on SoS with a mix of legacy systems, recently fielded systems, and future systems
  - How do we address already fielded systems to improve them
  - How do we rapidly assess new SoS that are assembled for a specific mission (mission engineering)
- Issues to address:
  - Computationally intensive for large, complex SoS
  - How do we V&V the results? What does it mean to have V&Ved results and are they useful?
  - How can this be automated to help rapidly field new SoS for new and developing missions?

Discussion

- The method helps to identify and mitigate spurious emissions before significant system design work has been completed
  - Leads to “good neighbors” in SoS and higher mission success
- Drawbacks and challenges
  - Computational requirements are potentially high
  - Lots of data is needed to have a high fidelity outcome
  - Decent understanding of SoS and of system is needed (will not easily work for “blue sky” designs with no heritage)
  - Uncertainty stackups can cause issues with making down-select decisions
- We advocate that humans still do V&V and be “in the loop” on analyzing and making decisions – not ready for prime time fully automated design

Limitations of Our Approaches

- Relies upon humans to decide if an event is possible or not
- Is derived based on historical data, which has (as always) uncertainty
- Assumes the FBD precedes the physical architecture
  - The method is intended to be used in early design when no physical architecture (of the system) has been developed
    - Allows for more flexibility in system redesign at the cost of less certainty in the probabilities of occurrence

Future Work

- Mission engineering perspective is needed on SoS “irrational behavior” of constituent members and on design of systems to repel and not emit spurious emissions
- Develop method of capturing preferences of engineers to fully automate design analysis process
- Examine flow levels and other advanced FFIP family of methods concepts to see how they may be more fully integrated into this methodology for more nuanced views of how systems and SoS behave

Conclusion

- We presented our work on a family of methods to identify potential spurious emissions at the functional level and figure out what to do about them from a SoS “good neighbor” perspective
- This helps us find low probability but high consequence spurious emissions before they find us
- All done during system architecture phase of SE process to reduce costs, improve outcomes, and decrease development time

Questions?

References

Method 1:

[1] Douglas L. Van Bossuyt, Ryan M. Arlitt. A Functional Failure Analysis Method of Identifying and Mitigating Spurious Emissions from a System of Interest in a System of Systems. ASME Journal of Computing and Information Science in Engineering. Accepted pending revisions November 2019, Submitted August 2019.

[2] Douglas L. Van Bossuyt, Ryan M. Arlitt. Toward a Functional Failure Analysis Method of Identifying and Mitigating Spurious System Emissions in a System of Systems. 2019 ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE2019.

Method 2:

[3] Douglas L. Van Bossuyt, Bryan M. O'Halloran, Ryan M. Arlitt. A Method of Identifying and Analyzing Irrational System Behavior in a System of Systems. Systems Engineering Journal, Accepted October 2019. In press.

[4] Douglas L. Van Bossuyt, Bryan M. O'Halloran, Ryan M. Arlitt. Irrational System Behavior in a System of Systems. IEEE 13th Annual System of Systems Engineering Conference, SoSE2018.

Method 3:

Coming soon!