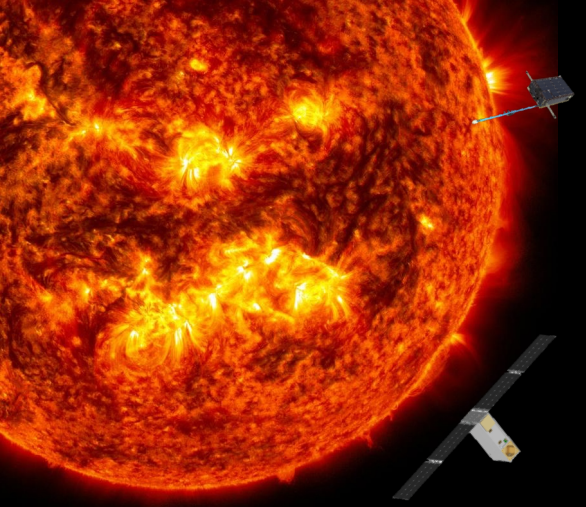
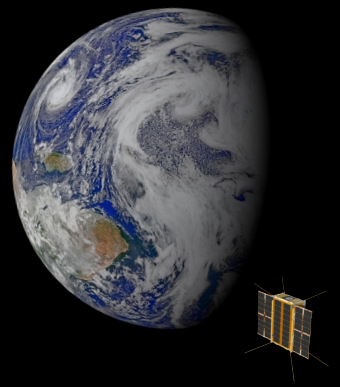
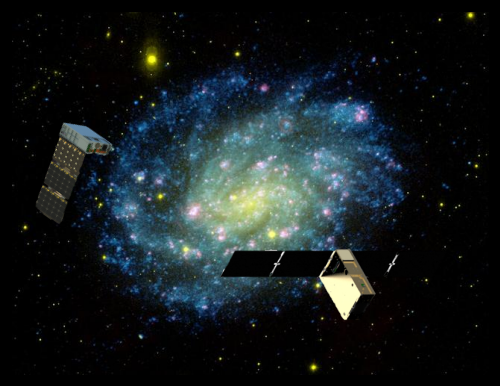
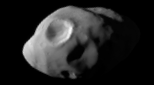
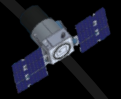





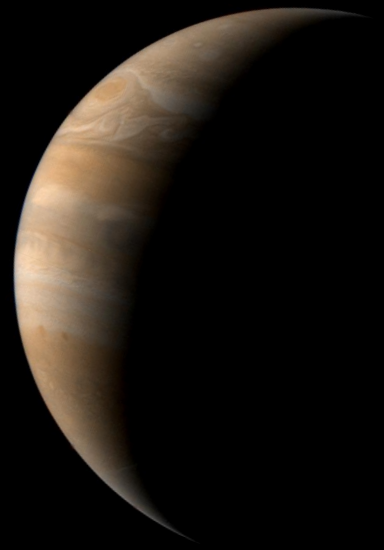
National Aeronautics and Space Administration

Autonomous System-Level Fault Diagnosis in Satellites using Housekeeping Telemetry



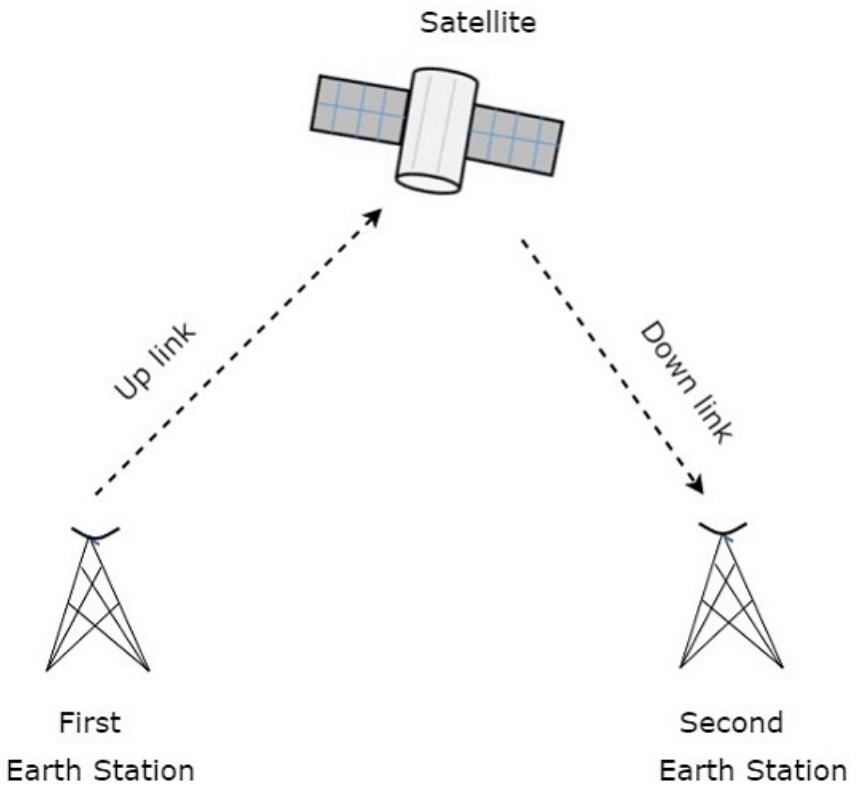
Evana Gizzi, Ph.D.*, Hayley Owens, Nicholas Pellegrino, Gabriel Rasskin, James Marshall*, Christopher Trombley*, Jivko Sinapov, Ph.D.

*NASA GSFC



Background and Motivation

Traditional Communication Paradigm for Spaceflight



"Satellite Communication - Services." *Tutorials Point - Satellite Communication Tutorial*

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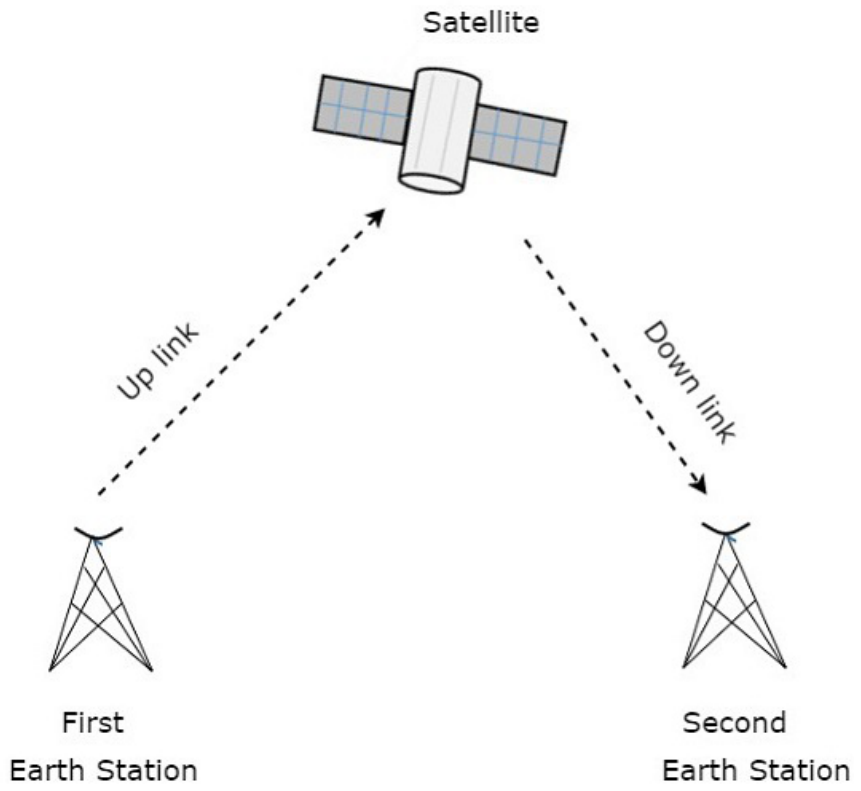

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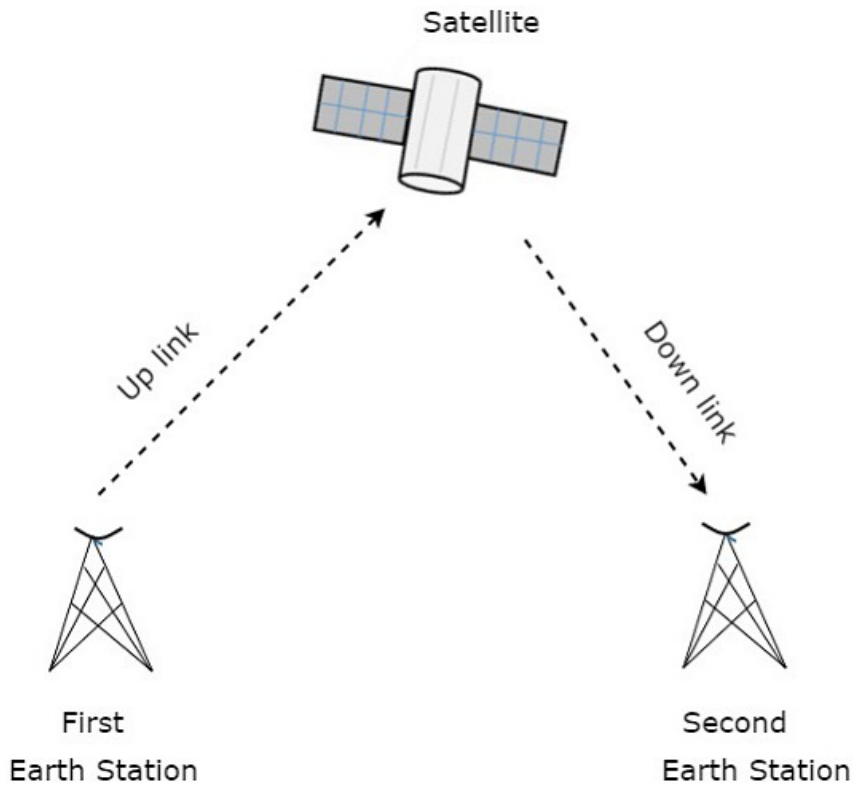
Limitations of Paradigm

Background and Motivation

Traditional Communication Paradigm for Spaceflight



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Limitations of Paradigm

- Time Delay
- Bandwidth
- Proximity

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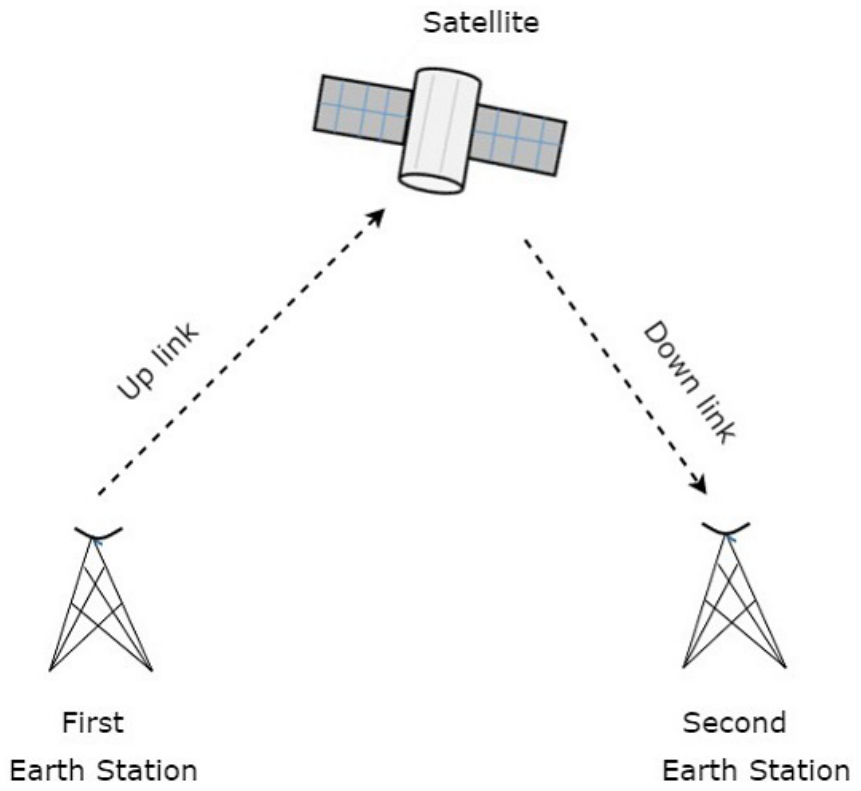

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Limitations of Paradigm

- Time Delay
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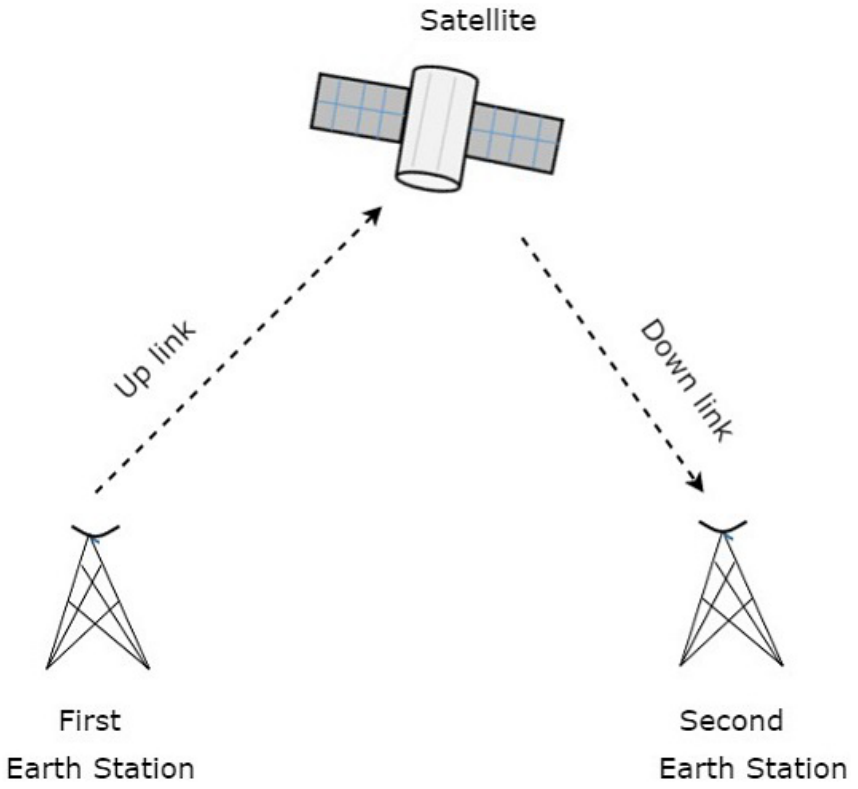
SCIENCE DATA LOSS

Background and Motivation

Safe Mode

SCIENCE DATA LOSS



"Satellite Communication - Services." *Tutorials Point - Satellite Communication Tutorial*

Limitations of Paradigm

- Time Delay
- Bandwidth
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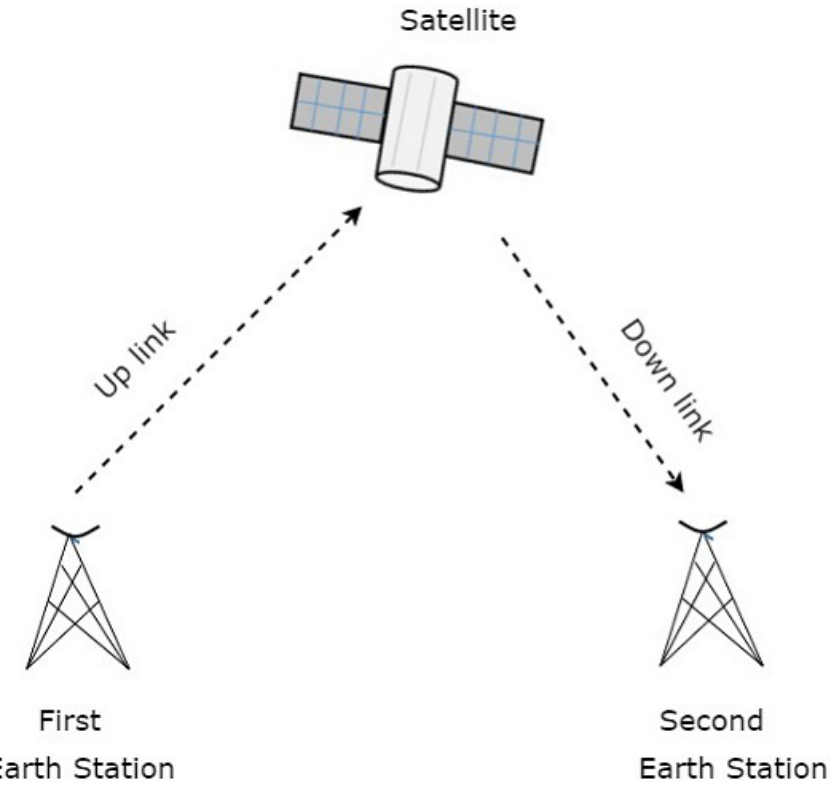
SCIENCE DATA LOSS

Background and Motivation

Safe Mode

SCIENCE DATA LOSS

- Onboard diagnosis rules for preemptively considered faults



"Satellite Communication - Services." *Tutorials Point - Satellite Communication Tutorial*

Limitations of Paradigm

- Time Delay
- Bandwidth
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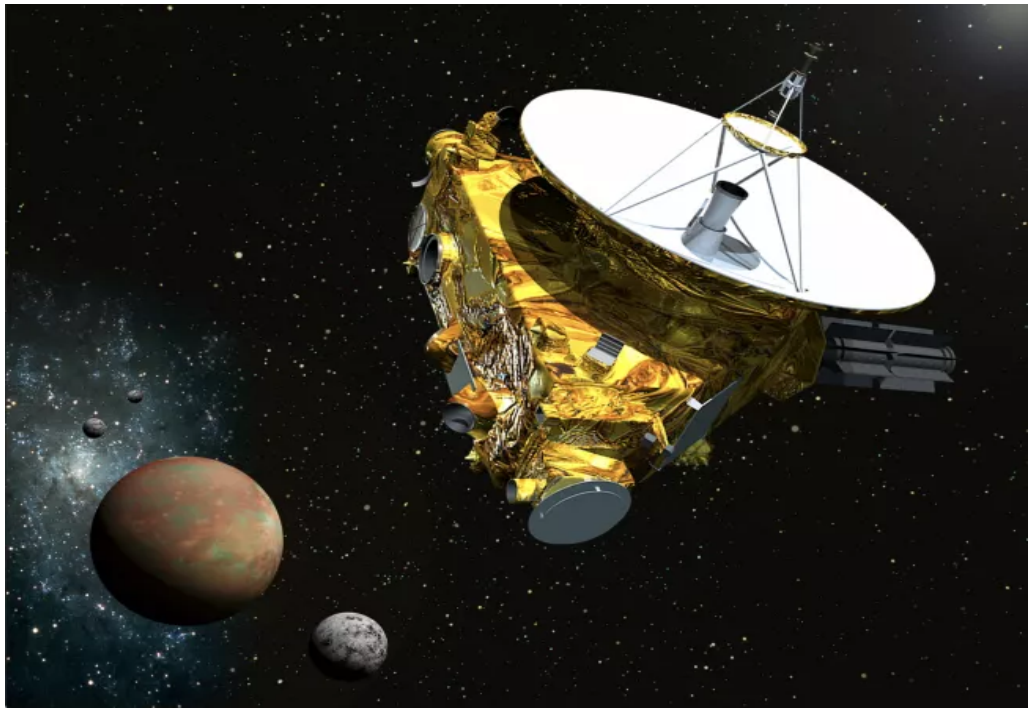
SCIENCE DATA LOSS

Background and Motivation

"The investigation into the anomaly that caused New Horizons to enter "safe mode" on July 4 has concluded that no hardware or software fault occurred on the spacecraft."



"NASA's New Horizons Plans July 7 Return to Normal Science Operations." NASA Blogs. Jul 5, 2015. Cofield, Calla, "NASA's New Horizons Spacecraft Wakes Up for Pluto Encounter in 2015." Space.com. December 7, 2014.

Grecius, Tony, "Mars 2020 Perseverance Healthy and on Its Way." NASA Blogs. July 30, 2020.

"We set the limits for the temperature differential conservatively tight for triggering a safe mode. The philosophy is that it is far better to trigger a safe mode event when not required, than miss one that is."

Research Goal

Research in Artificial Intelligence for Spacecraft Resilience

Contributors (civil servants, contractors, and interns)

Dr. Evana Gizzi [GSFC-587] Hayley Owens [GSFC-587-OSSI]
Dr. James Marshall [GSFC-587] Gabriel Rasskin [GSFC-587-OSSI]
Nicholas Pellegrino [GSFC-587-OSSI] Christopher Trombley [GSFC-587]
Jeff St. Jean [GSFC-587-OSSI] Caroline Kuzio [WFF-589]
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GOAL: Use Artificial Intelligence to intelligently diagnose the cause of a fault, given the symptoms.

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Important Consideration:

- Automation (nominal faults) versus Autonomy (anomalous faults)

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GOAL: Use Artificial Intelligence to intelligently diagnose the cause of a fault, given the symptoms.

Important Consideration:

- Automation (nominal faults) versus Autonomy (anomalous faults)

Enables:

- Fully autonomous spaceflight
- Development of next-gen flight paradigms

Preliminaries

Main AI constructs used:

- Kalman Filters
- Autoencoders
- Causality

Preliminaries

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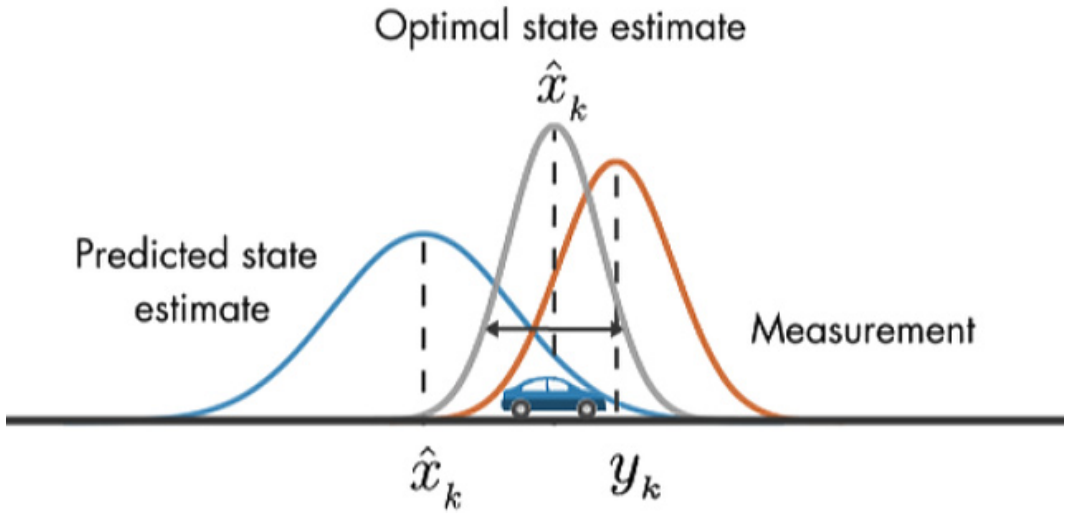
How "broken" is a mnemonic, relative to itself?



https://www.mathworks.com/videos/understanding-kalman-filters-part-3-optimal-state-estimator--1490710645421.html

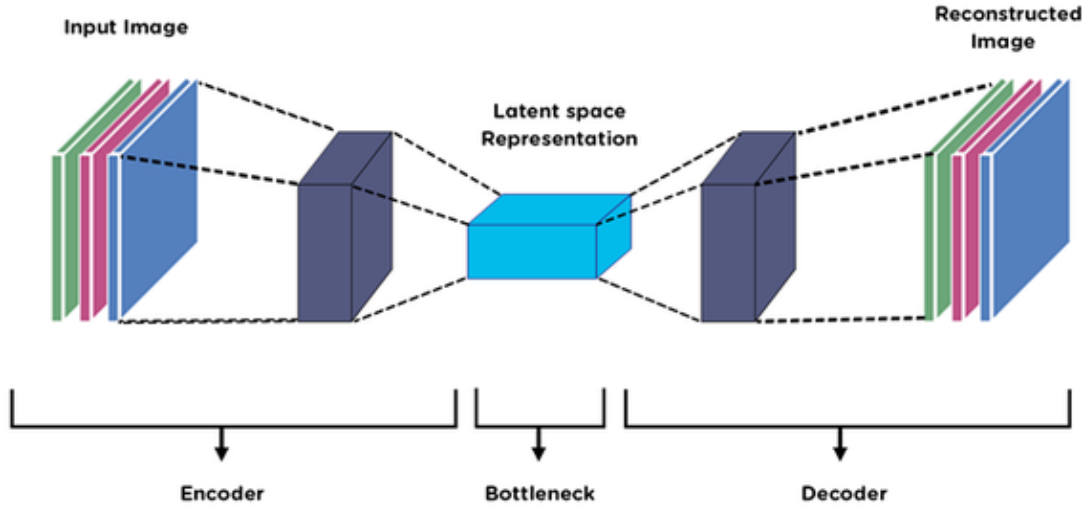
- Dynamic linear estimation models able to provide a prediction from previously measured data
- Account for noise in sensor readings

Preliminaries

Main AI constructs used:

- Kalman Filters
- Autoencoders
- Causality

How "broken" is a mnemonic, relative to the telemetry landscape? (contextual)



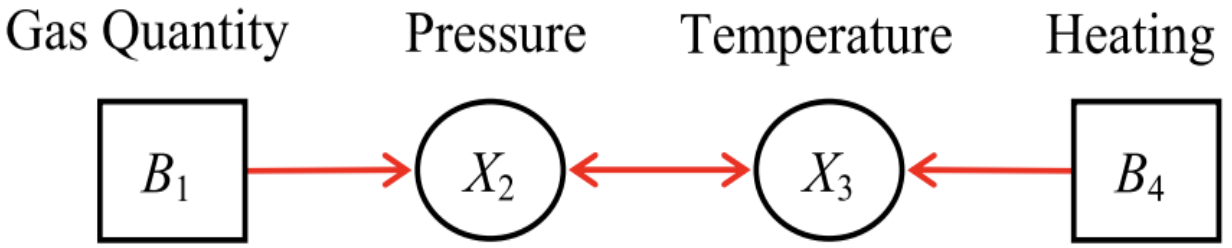
https://medium.com/@birla.deepak26/autoencoders-76bb49ae6a8f

- Unsupervised neural network representation learners
- Can encode information into a latent space representational form, and decode latent space back into original high dimensional form
- Used **Shapley Values** and reconstruction error

Preliminaries

Main AI constructs used:

- Kalman Filters
- Autoencoders
- Causality

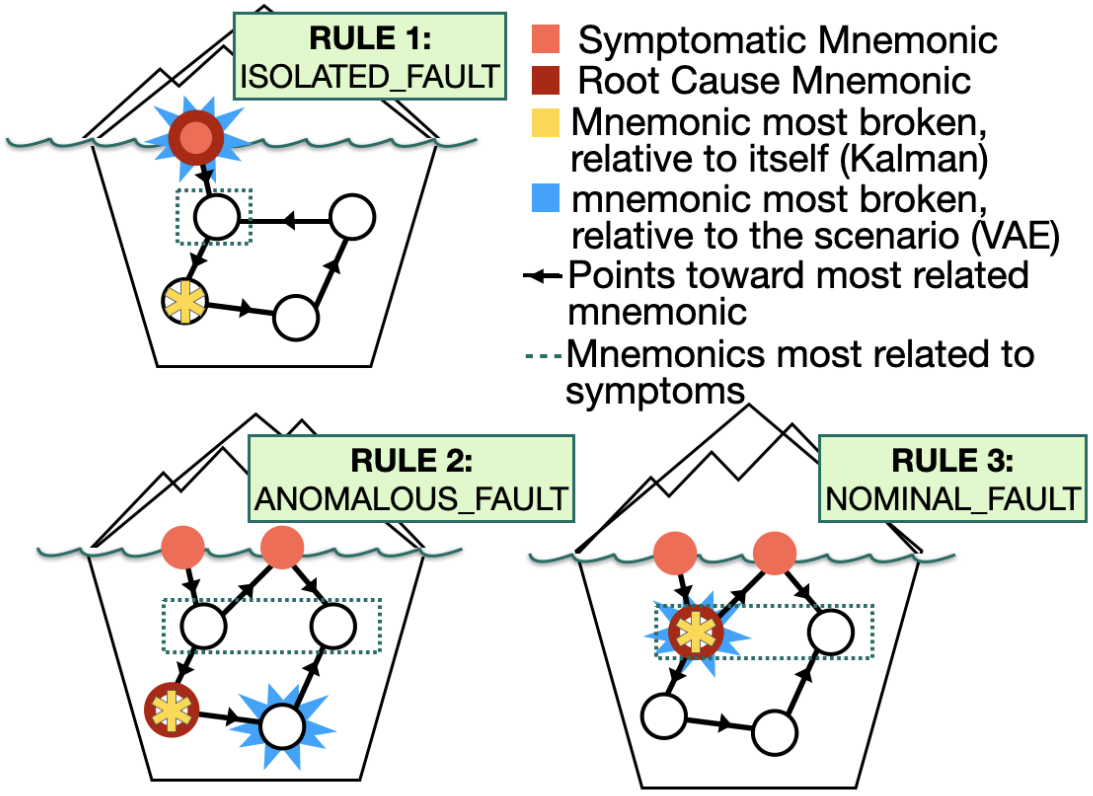


Zhang, Q., Dong, C., Cui, Y., & Yang, Z. (2013). Dynamic uncertain causality graph for knowledge representation and probabilistic reasoning: statistics base, matrix, and application. IEEE Transactions on Neural Networks and Learning Systems, 25(4), 645-663.

Which mnemonics are related to which other mnemonics, in an "instantaneous" sense?

- Measures the level of directional "instantaneous relatedness" among mnemonics
- Utilizes conditional probabilities and derivatives (do-calculus) to capture event changes
- Similar to traditional correlation calculation, with more restrictions to induce causal relationships

Classes of Faults



ISOLATED_FAULT:

- Single event upsets (SEUs)
- Bit flips

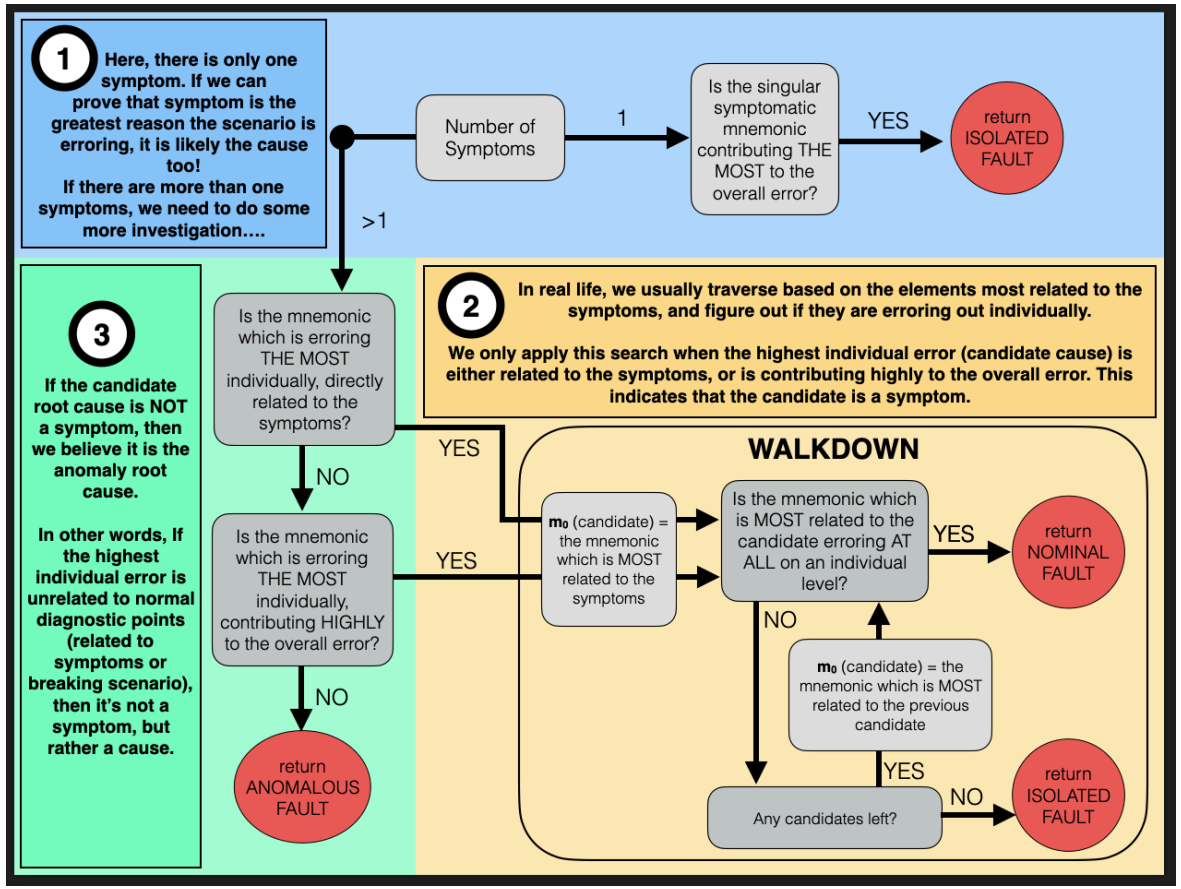
NOMINAL_FAULT:

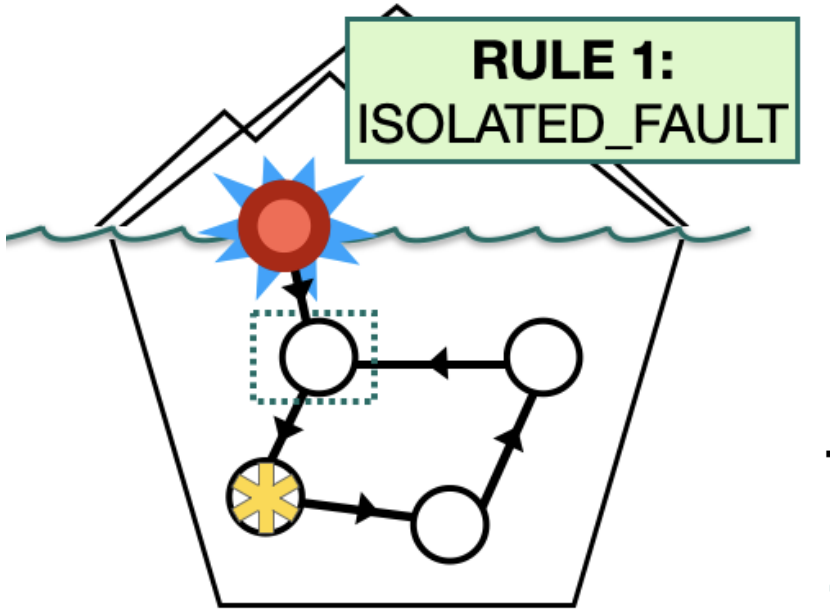
- Preemptively considered faults
- "Run of the mill"

ANOMALOUS_FAULT:

- Unexpected/unforeseen faults
- No past data showing similar scenarios

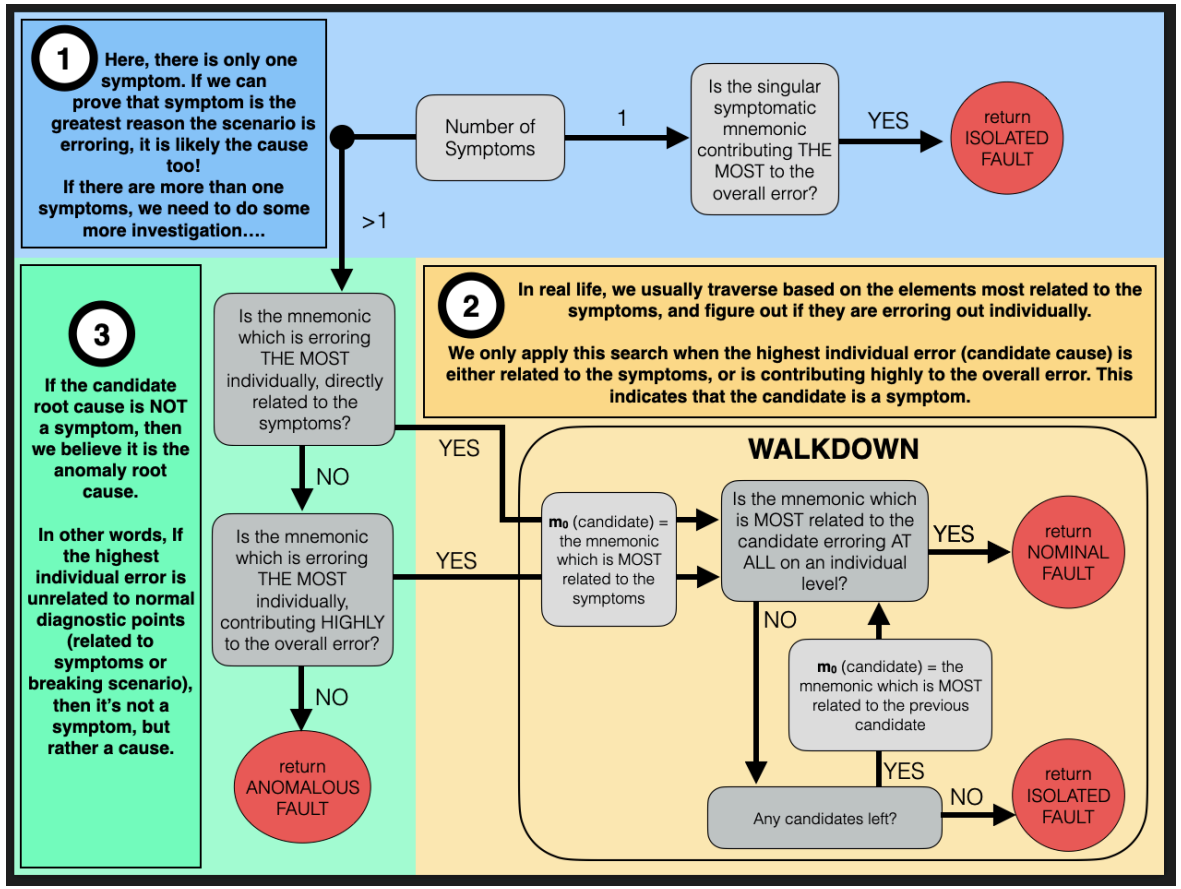
Diagnosis Algorithm

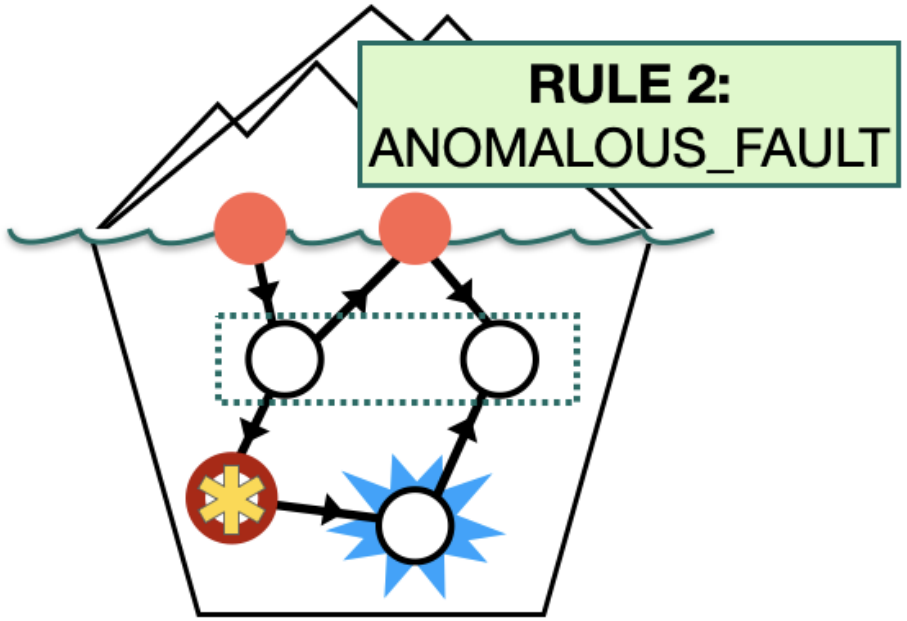




- Only one symptom, which is contributing the most to overall error

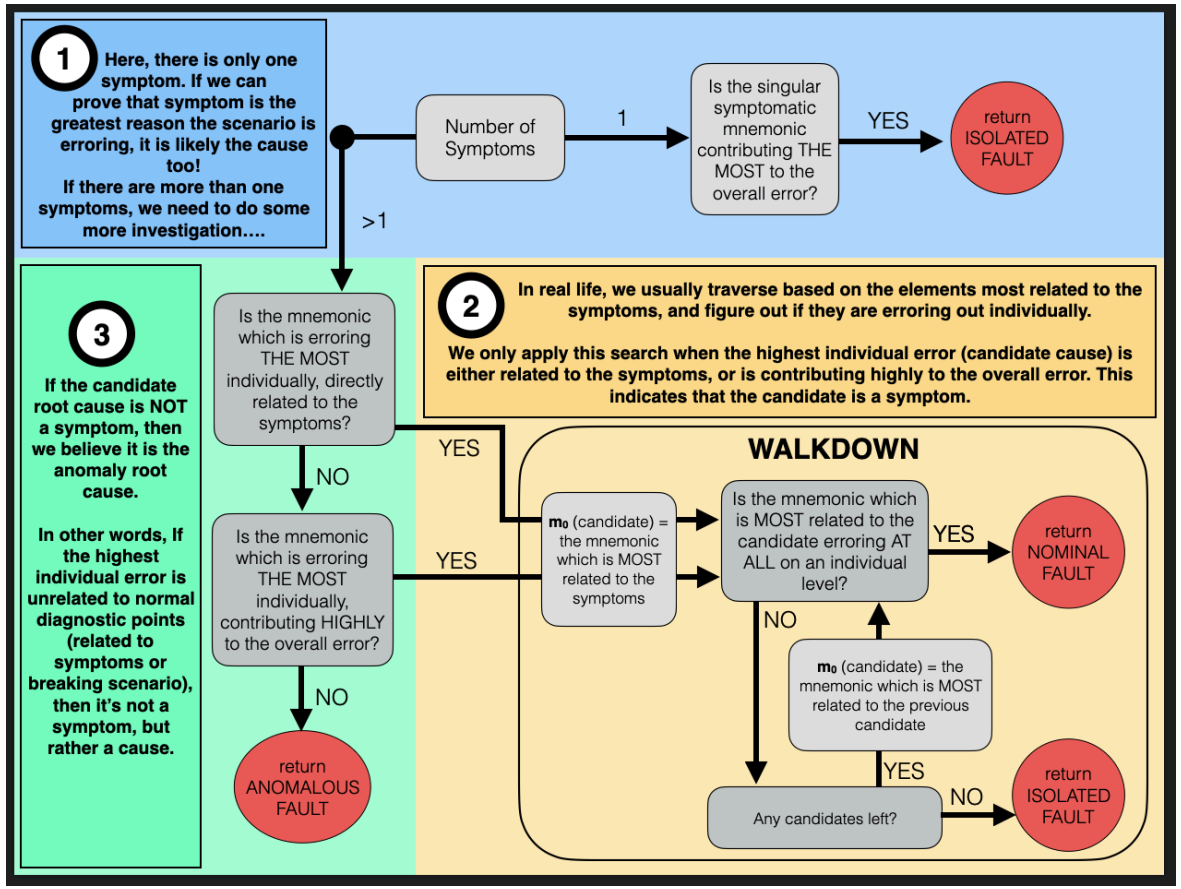
Diagnosis Algorithm

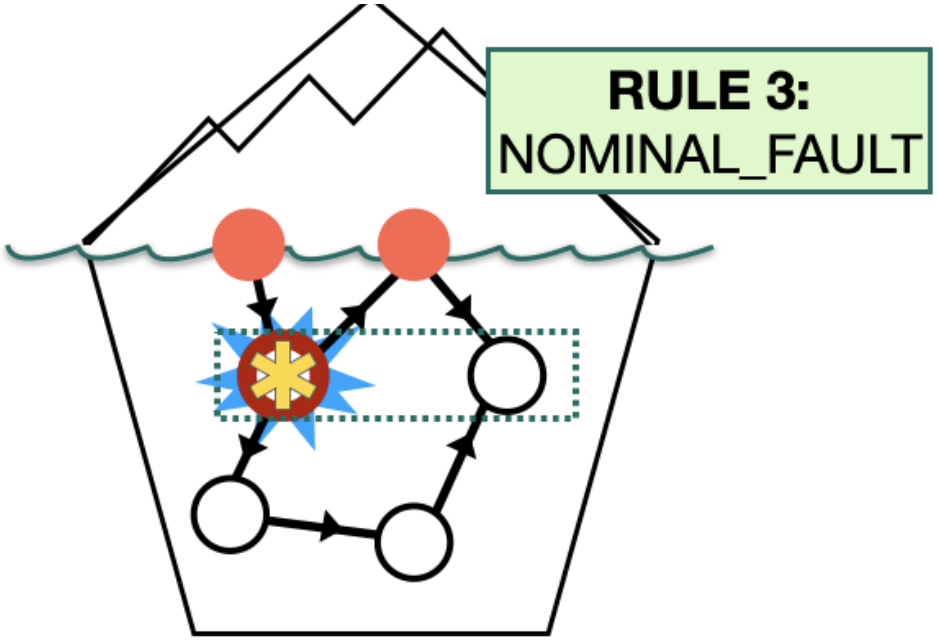




- Highest individually faulting mnemonic is not well-connected to symptoms or alternative candidate symptoms

Diagnosis Algorithm





- Walkdown strategy involves traversal of mnemonics most related to symptoms until individual error is found in graph

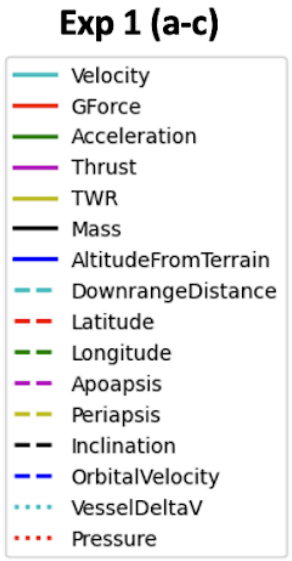
Outcomes: Software Platform

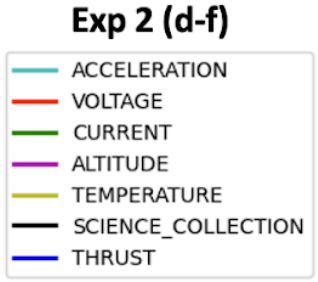
		Mission Length	Frame Size
Exp #	# Missions	[min, max], sd	# Mnemonics
1	11	[1440,1440],0	8
2	10	[651,2028],554.9	17
3	1	[6448,6448],0	33

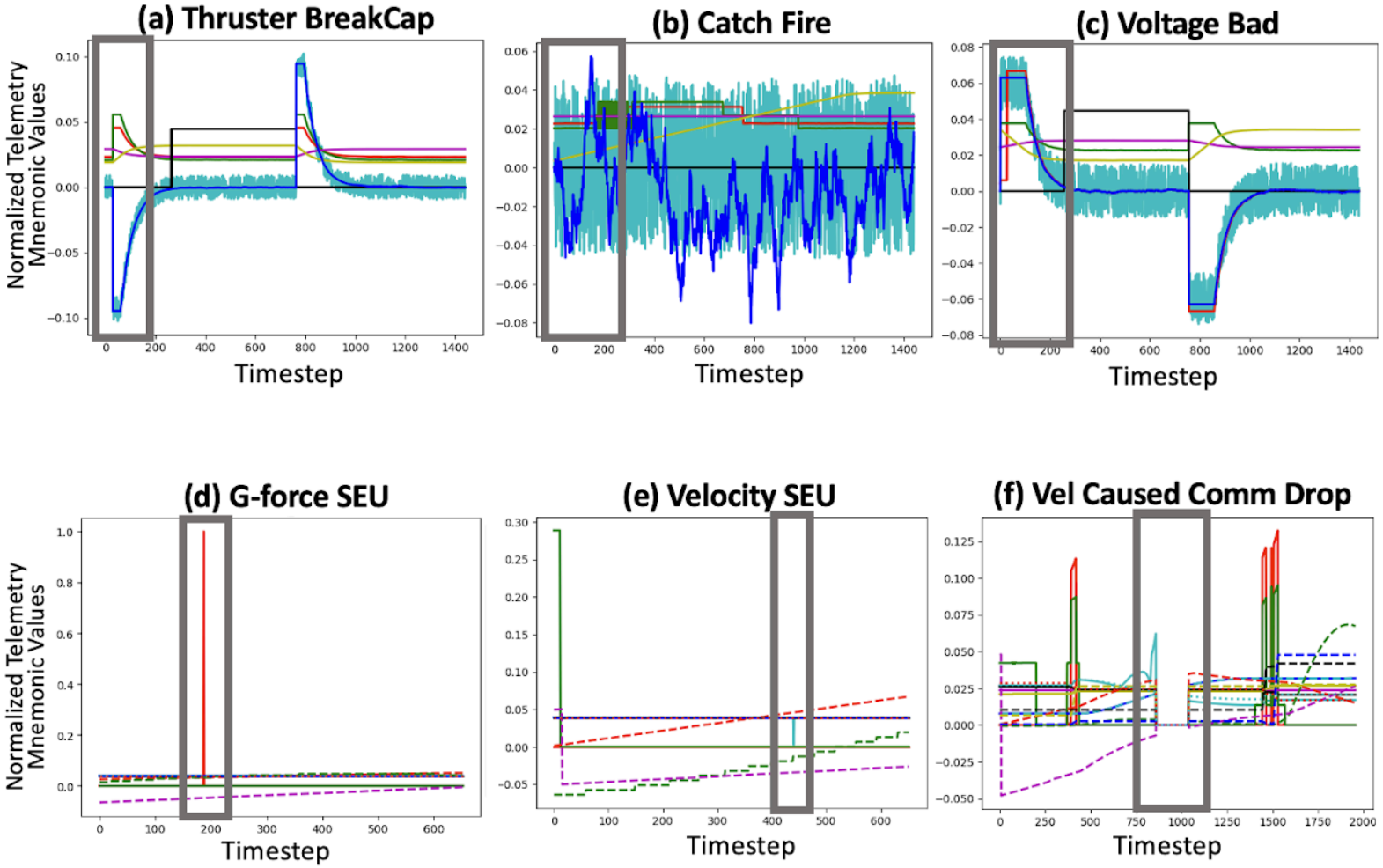
		Reinforcement Learning (Proximal Policy Optimization)		Machine Learning (Autoencoders)		
Ex #	Acc	PPO-1	PPO-2	AE-1	AE-2	WD
1	0.77	0.03	0.04	0.35	0.60	0.64
2	0.70	0	0	0.48	0.53	0.3

- Performance tested on four datasets of varying complexity levels (three shown here)
- Baseline Tested against state of art AI approaches (0.7 vs 0.55 in worst case performance of RAISR)

Outcomes: Software Platform







Outcomes: Hardware Platform

Construct	10 mpf	50 mpf	100 mpf	200 mpf
Kalman	0.237ms	0.351ms	0.581ms	0.831ms
VAE	0.211ms	0.589ms	1.05ms	1.98ms
Causality	0.845ms	4.5ms	5.05ms	5.42ms

- Benchmark Tests on Raspberry Pi ARM architecture (COVID contingency plan)
- Ablation Study on constituent parts

Current Work

Fault Mitigation for Distributed Systems Mission (DSM) Design Concept

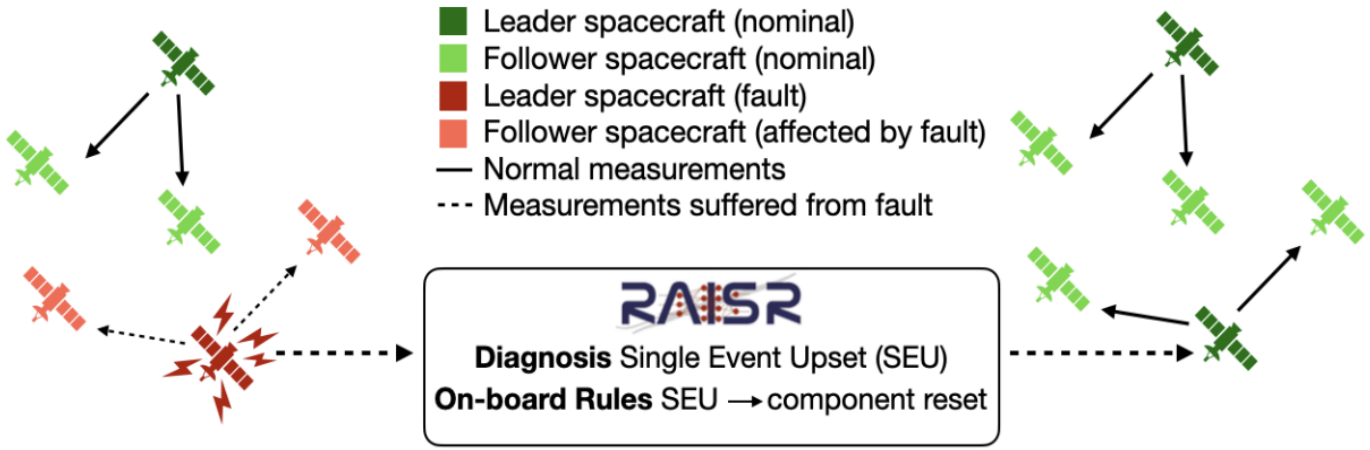


Figure: Depiction of RAISR resolving a fault in a traditional single leader-follower multi-agent system (MAS) navigation structure

https://spaceflight.com/spaceflight-inc-signs-multi-launch-agreement-with-hawkeye-360/

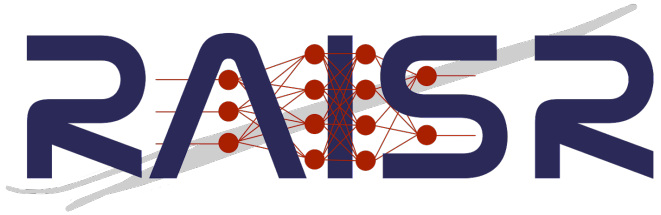
- Continued development of single-case fault diagnosis
- Adaptation to multi-agent use case
- Interested in external collaboration

Summary

https://spaceflight.com/spaceflight-inc-signs-multi-launch-agreement-with-hawkeye-360/

- Fault diagnosis is a necessary step toward
  - Resilient space flight (true autonomy)
  - Enabling next-gen space flight, like constellation missions
- Limitations
  - Quality of data (diversity, curation, amount)
- Future Work
  - Broaden RAISR to “system resilience”
  - Boost TRL through DSM

Thank you!



Thank You! Question?