



Physics-Guided Deep Learning for Complex System Health Management and Decision Making

Chetan S. Kulkarni

KBR Inc, NASA Ames Research Center
Diagnostics and Prognostics Group

Project Overview



NASA's System-Wide Safety (SWS) project is developing innovative data solutions to assure safe, rapid, and repeatable access to a transformed National Airspace System (NAS).

1. Created in 2018 and is part of NASA Aeronautics' Airspace Operations and Safety Program.
2. Evaluates how the aerospace industry and aircraft modernization impacts safety by using technology to address future operational and design risks.

SWS Goals:

1. To explore, discover, and understand the impact on safety of growing complexity introduced by modernization aimed at improving the efficiency of flight, the access to airspace, and the expansion of services provided by air vehicles
2. To develop and demonstrate innovative solutions that enable this modernization and the aviation transformation envisioned for global airspace system through proactive mitigation of risks in accordance with target levels of safety



System-Wide Safety

Project Overview (cont)



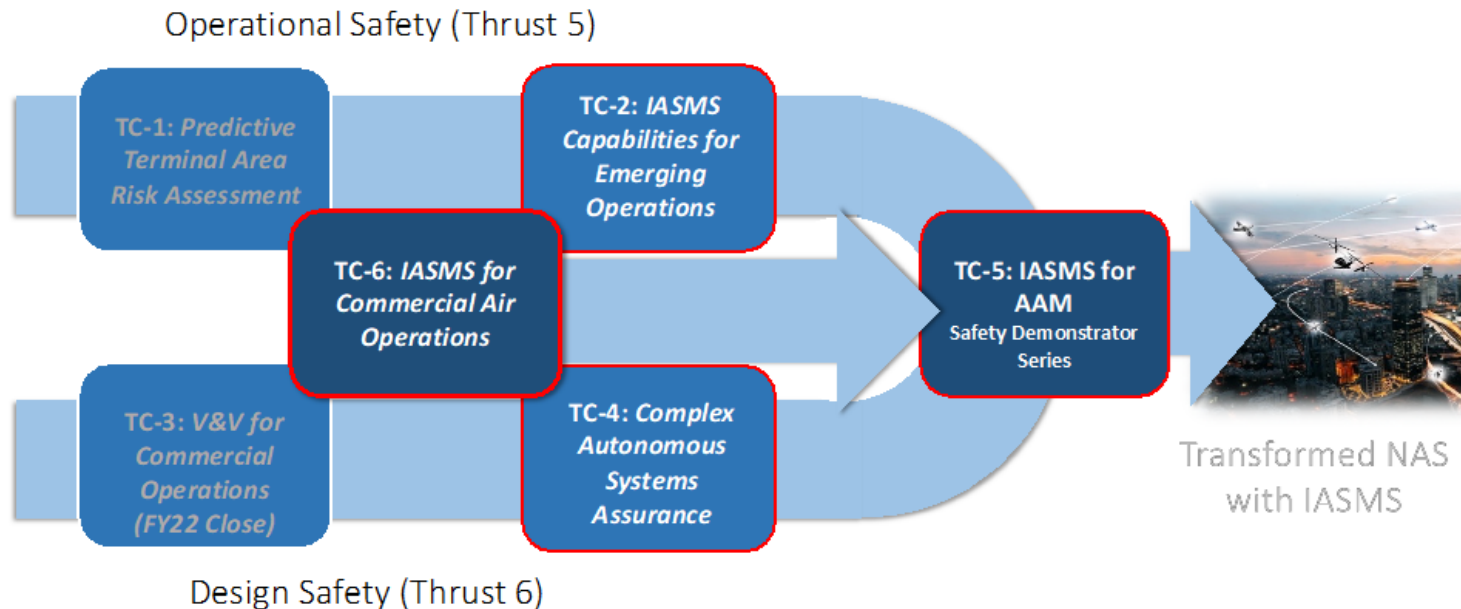
To transform the NAS, SWS employs high-risk research and development (R&D) to understand how the modernization of industry and aircraft can affect overall safety. SWS is developing and demonstrating innovative solutions within several key research areas, referred to as technical challenges.

Current Technical Challenges (TCs):

- **TC-2: In-Flight Safety Predictions for Emerging Operations**
 - TC-4: Complex Autonomous Systems Assurance
 - **TC-5: Safety Demonstrator Series for Operational IASMS**
 - TC-6: In-Time Aviation Safety Management System
-
- SWS is developing the concept and requirements for an assured In-Time Aviation Safety Management System (IASMS) to achieve the goals described above.
 - An IASMS is an integrated set of services, functions, and capabilities (SFCs) to address operational risks and hazards of a transformed NAS. SWS catalyzes the discovery of the unknown and paves the path forward for aviation safety in the future airspace.



SWS Project Research Portfolio



SWS Project Research Portfolio



As a project within the Airspace Operations and Safety Program of NASA's Aeronautics Research Mission Directorate, System-Wide Safety's research will:

- Improve the efficiency of flight, the access to airspace, and the expansion of services provided by air vehicles.
- Explore, discover, and understand the impact on safety from the growing complexity introduced by industry modernization.
- Develop and demonstrate innovative solutions that enable the aviation transformation envisioned for global airspace system.
- Identify and proactively mitigate risks per target levels of safety



System-Wide Safety

Innovating the Future of Aviation

Human-Centric Capabilities

Safety + Density

Human centered traffic &
Safety management



Digitally Transformed Infrastructure

Collaborative Environment

Service oriented
architecture
for tailored mission services
+ ML
+ IoT

xTM
Provider of Services

FAA
Industry Data
Exchange

Automation-Enabled Diversity

Highly Automated

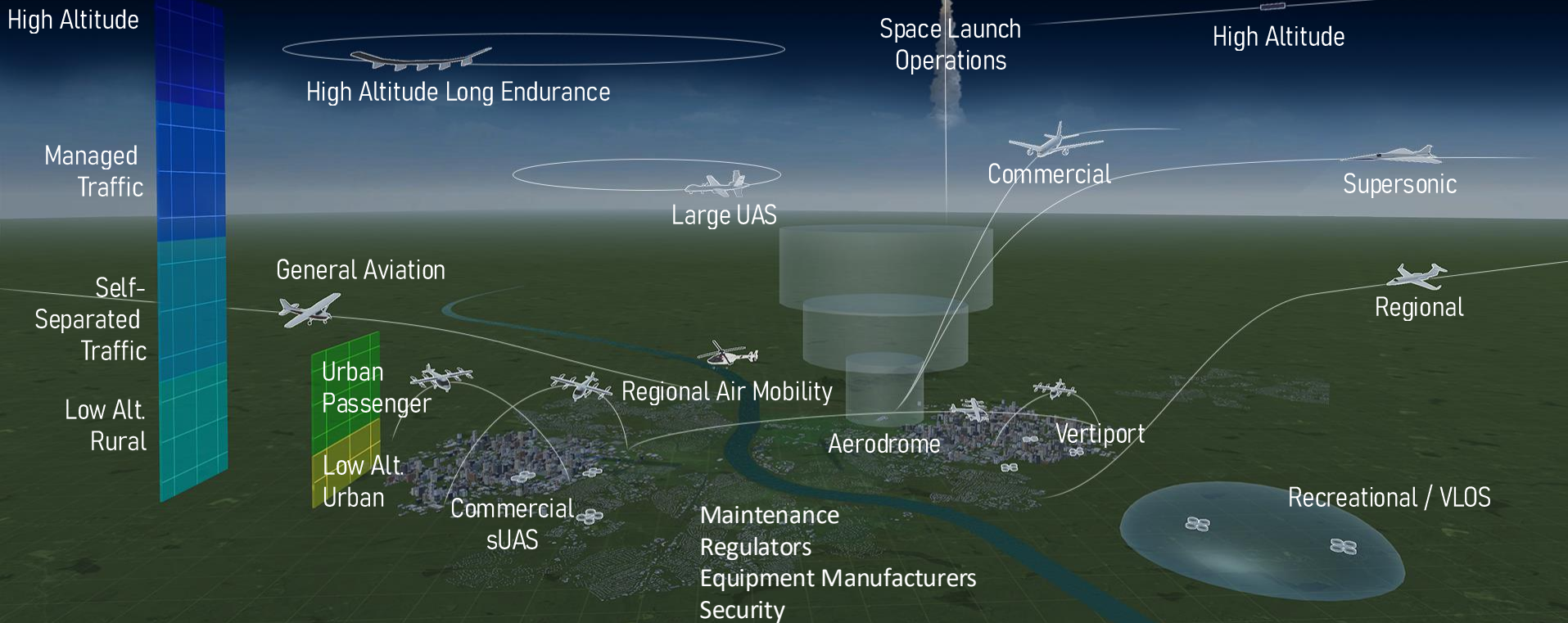
Complexity, scalability,
And dynamic adaptation
+ digital mesh
+ AI
+ IoT



Evolution of Airspace Operations and Safety



Variety of Aviation Participants



Transformed Airspace *A Complex Challenge*

More Operations = Increased risk potential

New Missions = Increased Integration Complexity

Sustainability = New Constraints

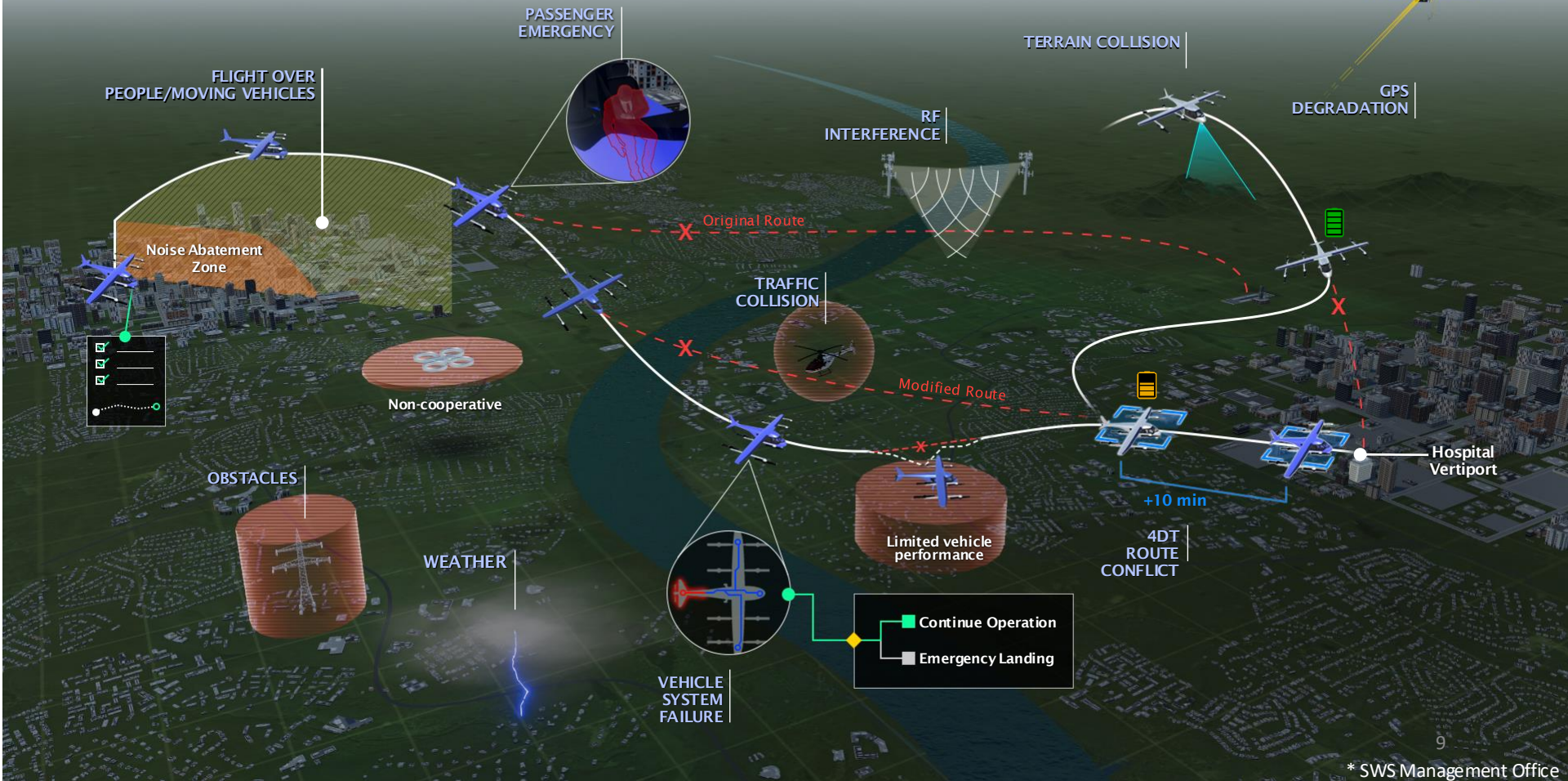
Notable Barriers

Digital Transformation – Changes to Existing Systems and Integration of New Systems is a Known Challenge

AAM – Certification and Paths Needed for both Airworthiness and Operations

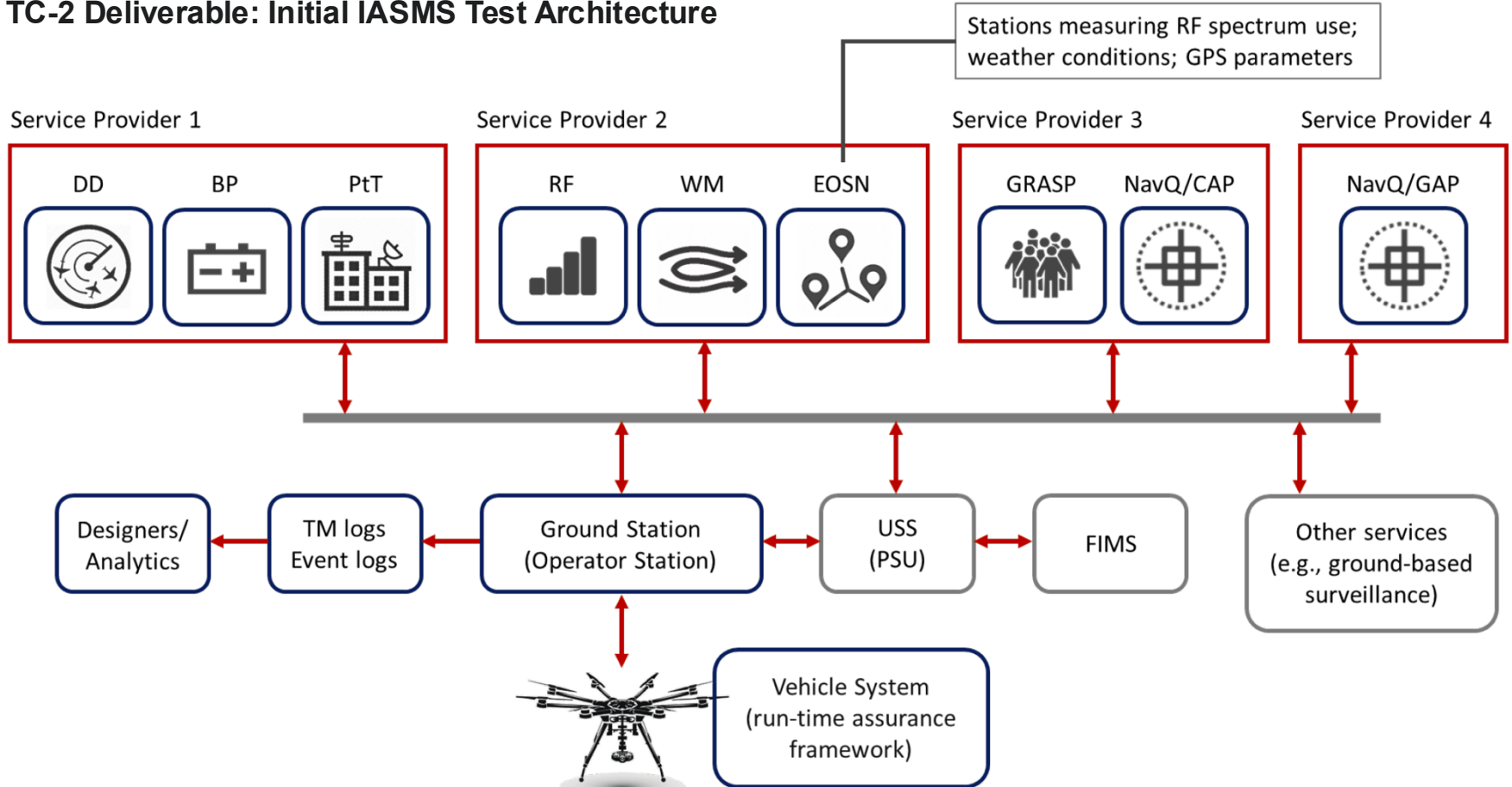
Automation and Autonomy – Means of Assuring Automated/Autonomous Systems a looming challenge

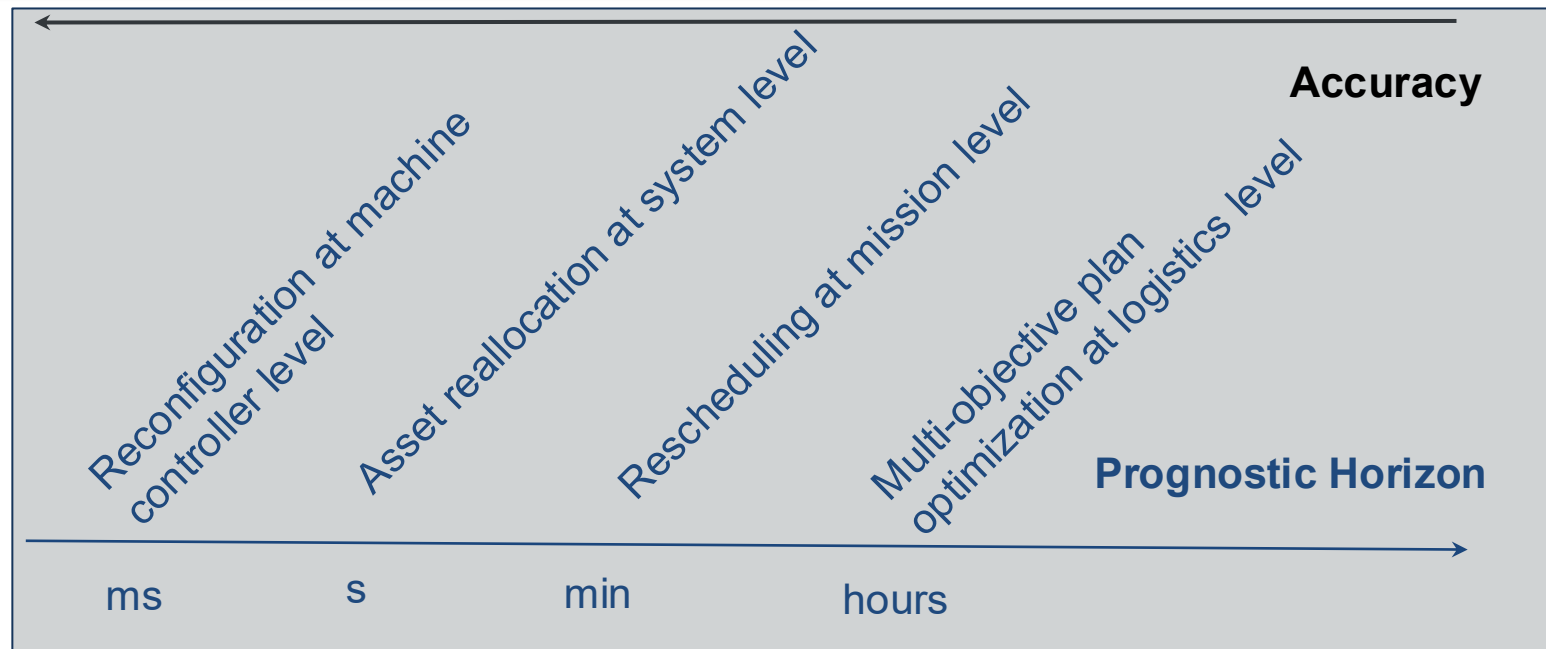
Complexities, Risks and Constraints



Background

TC-2 Deliverable: Initial IASMS Test Architecture



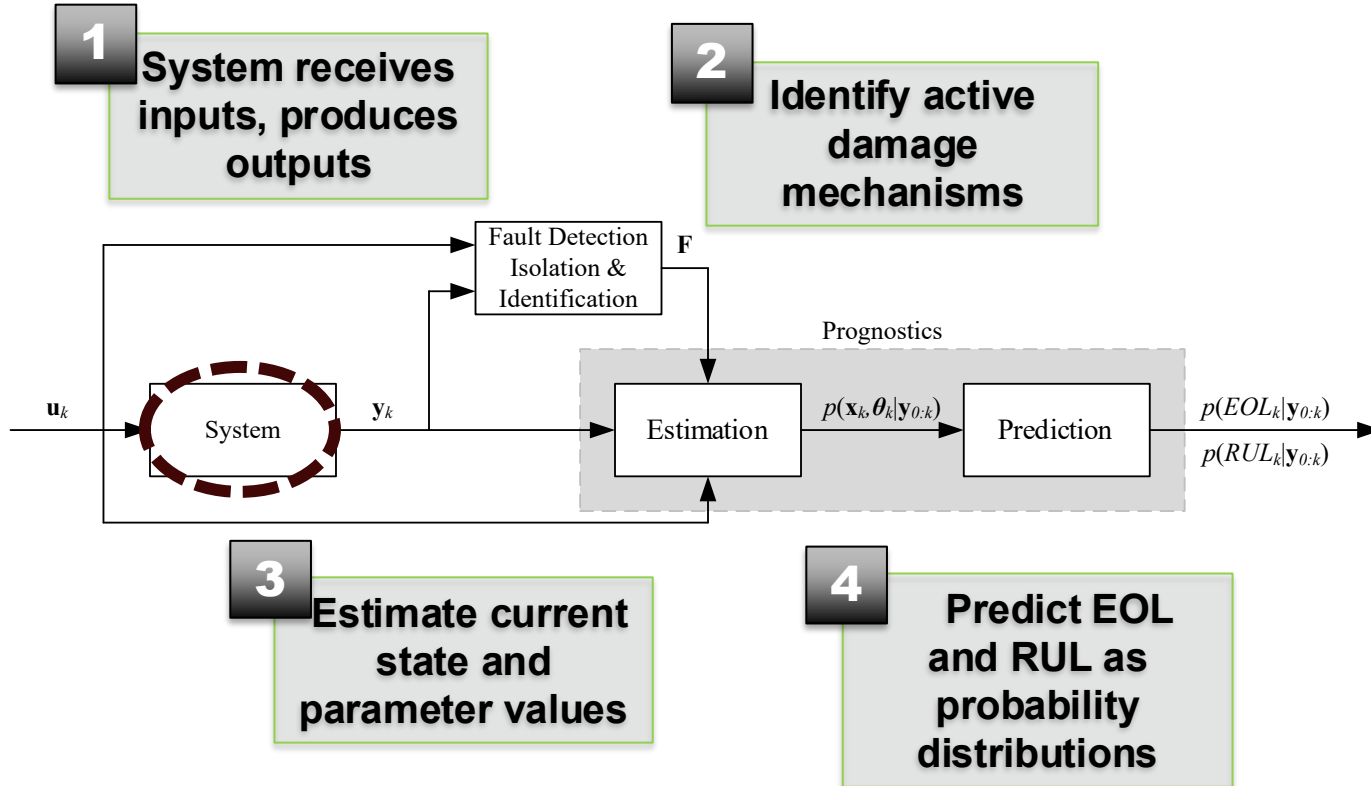


Autonomy

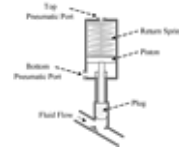
Pilots / Air Traffic Control

Airline Operators

Maintenance



- Model underlying physics of a component/subsystem



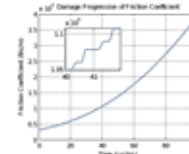
$$f_p(p_1, p_2) = \begin{cases} C_p A_p \sqrt{\frac{\gamma}{2R_p T} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} (p_1^{1/\gamma} - p_2^{1/\gamma})} & p_1 \geq p_2 \wedge p_1/p_2 \geq \left(\frac{\gamma+1}{\gamma-1} \right)^{\gamma/(\gamma-1)} \\ C_p A_p \sqrt{\frac{\gamma}{2R_p T} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \left(\left(\frac{p_1}{p_2} \right)^{2/\gamma} - \left(\frac{p_1}{p_2} \right)^{1/\gamma} \right)} & p_1 \geq p_2 \wedge p_1/p_2 < \left(\frac{\gamma+1}{\gamma-1} \right)^{\gamma/(\gamma-1)} \\ C_p A_p \sqrt{\frac{\gamma}{2R_p T} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} (p_2^{1/\gamma} - p_1^{1/\gamma})} & p_1 < p_2 \wedge p_2/p_1 \geq \left(\frac{\gamma+1}{\gamma-1} \right)^{\gamma/(\gamma-1)} \\ C_p A_p \sqrt{\frac{\gamma}{2R_p T} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \left(\left(\frac{p_2}{p_1} \right)^{2/\gamma} - \left(\frac{p_2}{p_1} \right)^{1/\gamma} \right)} & p_1 < p_2 \wedge p_2/p_1 < \left(\frac{\gamma+1}{\gamma-1} \right)^{\gamma/(\gamma-1)} \end{cases}$$

- Model physics of damage propagation mechanisms



$$f_t(t) = f_g(p_t(t), u_t(t))$$

$$f_b(t) = f_g(p_b(t), u_b(t))$$



$$f_v(t) = \frac{x(t)}{L_R} C_v A_v \sqrt{\frac{2}{\rho}} |p_{f1} - p_{fr}| \text{sign}(p_{f1} - p_{fr})$$

$$\hat{r}(t) = w_r |F_f(t)| v(t)$$

- Determine criteria for End-of-Life threshold



$$EOL(t_P) \triangleq \inf\{t \in \mathbb{R} : t \geq t_P \wedge T_{EOL}(\mathbf{x}(t), \boldsymbol{\theta}(t)) = 1\}$$

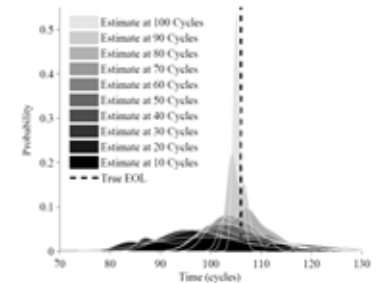
- Develop algorithms to propagate damage into future

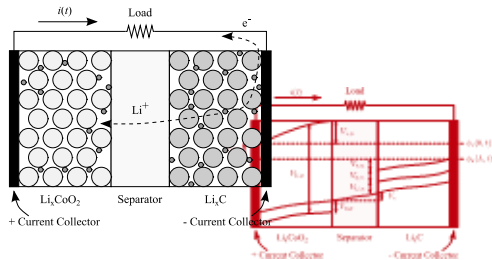
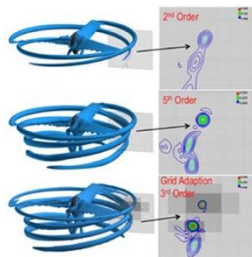
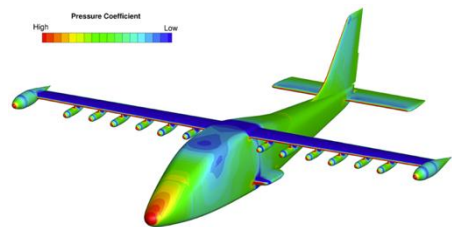


Algorithm 2 EOL Prediction

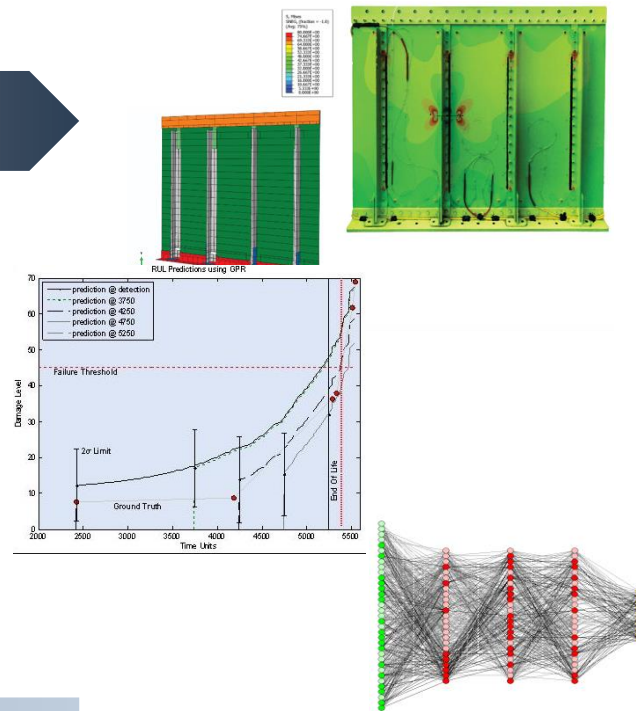
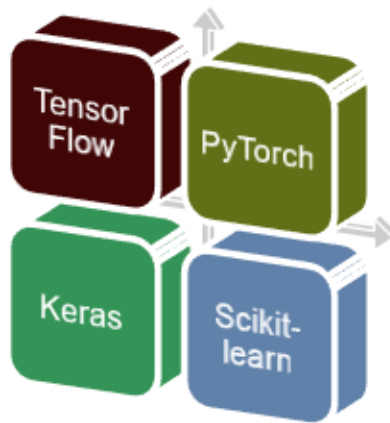
Inputs: $\{(\mathbf{x}_{i,p}^*, \boldsymbol{\theta}_{i,p}^*, w_{i,p}^*)\}_{i=1}^N$
Outputs: $\{EOL_{i,p}, w_{i,p}\}_{i=1}^N$
for $i = 1$ **to** N **do**
 $k \leftarrow k_P$
 $\mathbf{x}_k^* \leftarrow \mathbf{x}_{i,p}^*$
 $\boldsymbol{\theta}_k^* \leftarrow \boldsymbol{\theta}_{i,p}^*$
while $C_{EOL}(\mathbf{x}_k^*, \boldsymbol{\theta}_k^*) = 0$ **do**
 Predict $\hat{\mathbf{u}}_k$
 $\boldsymbol{\theta}_{k+1}^* \sim p(\boldsymbol{\theta}_{k+1} | \boldsymbol{\theta}_k^*)$
 $\mathbf{x}_{k+1}^* \sim p(\mathbf{x}_{k+1} | \mathbf{x}_k^*, \boldsymbol{\theta}_k^*, \hat{\mathbf{u}}_k)$
 $k \leftarrow k + 1$
 $\mathbf{x}_k^* \leftarrow \mathbf{x}_{k+1}^*$
 $\boldsymbol{\theta}_k^* \leftarrow \boldsymbol{\theta}_{k+1}^*$
end while
 $EOL_{i,p} \leftarrow k$
end for

- Deal with uncertainty





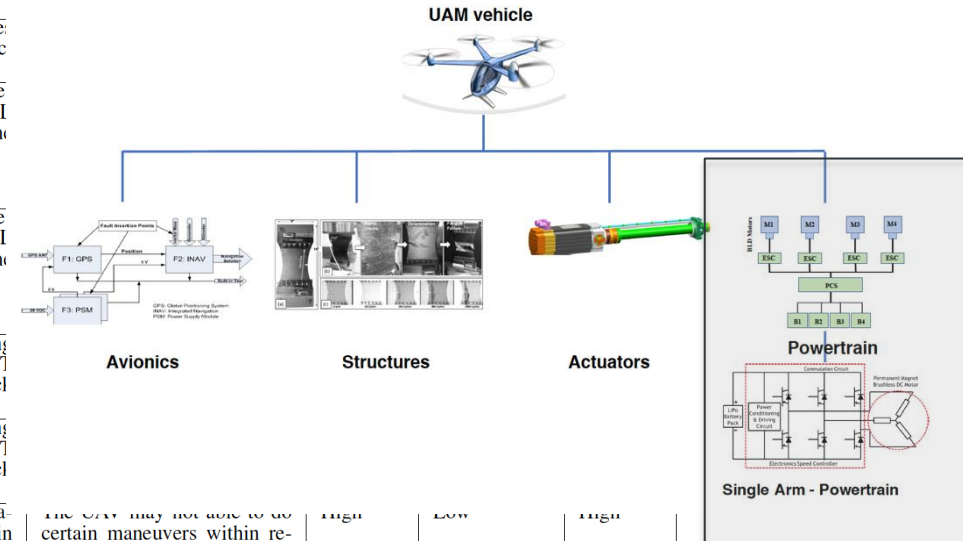
Machine-Learning underlying physics parameters

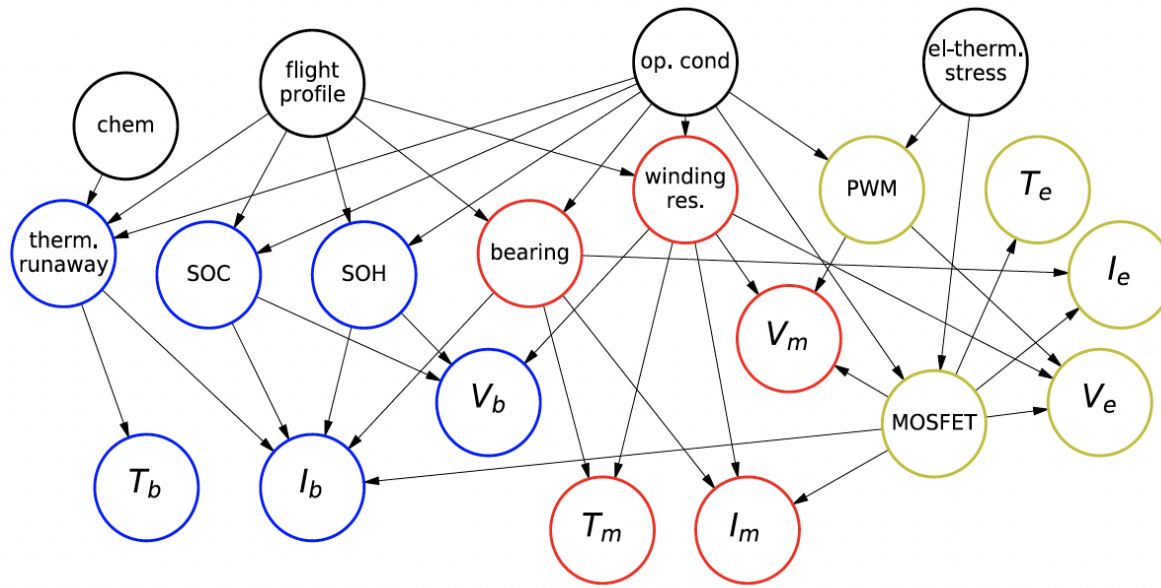


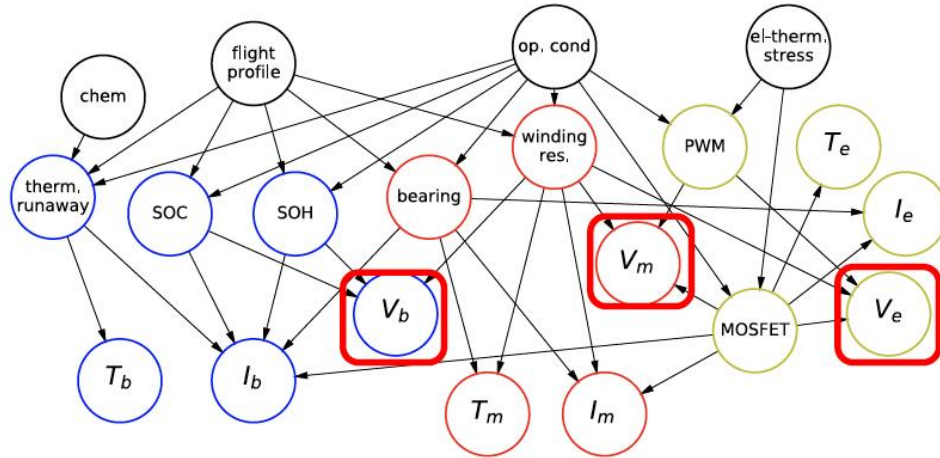
Understanding and Learning underlying Physics for Complex Systems

Diagnostics

Component	Faults	Root Cause	Effect on UAV	Effect on Airspace	Severity	Probability of Occurrence	Safety Critical
Battery Pack	SOC	Operational Conditions	Directly affects operation of the power train system	In case the SOC goes below set low threshold and UAV is not able to do a safe landing may violate safety with crash landing/ may interfere in path of other UAV	High	High	High
Battery Pack	SOH	Operational conditions, loading profiles	Aging in the batteries may not directly affect other systems	The UAV may not able to do certain maneuvers within required time period	High	High	High
Motor (Single)	Low insulation resistance	Operational conditions, loading profiles	Aging in the batteries may not directly affect other systems	The UAV may not able to do	High	High	High
Motor (Single)	Bearing Faults, mass unbalance	Operational conditions, loading profiles	Aging in the batteries may not directly affect other systems				
Motor (Single)	Power Consumption	change in winding resistance, bearing faults	High draw currents decrease the battery RUI shortening flight time considerably				
Motor (Multiple)	Power Consumption, Low insulation resistance, bearings	change in winding resistance, bearing faults	High draw currents decrease the battery RUI shortening flight time considerably				
ESC (Single)	Power Consumption	operational stress, High electrical, thermal stress on the components	Change in switching frequency, MOSFET degradation, structural faults				
ESC (Multiple)	Power Consumption	operational stress, High electrical, thermal stress on the components	Change in switching frequency, MOSFET degradation, structural faults				
CES	Filtering Capacitor/MOSFET failures	Operational stress, High electrical, thermal stress on the components	Directly affects operation of the power train system	The UAV may not able to do certain maneuvers within required time period and flight profile	High	Low	High







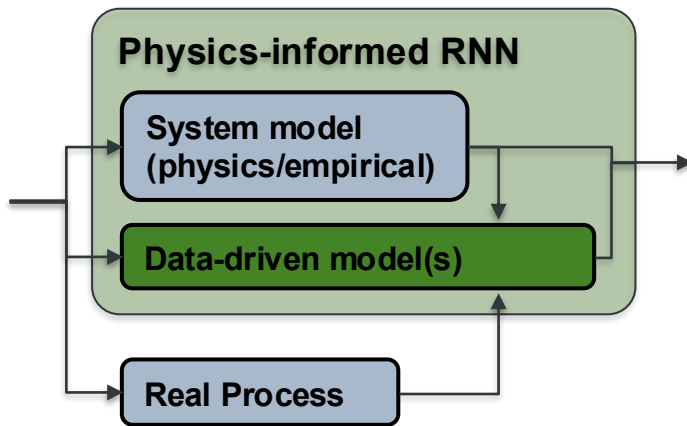
Anomalous voltages readings
 $V_b = V_e = V_m = 1$

$$\begin{aligned} \Pr\{\text{SOC} = 1 | V_b, V_e, V_m\} &= 0.82021 & \leftarrow 1 \\ \Pr\{\text{SOH} = 1 | V_b, V_e, V_m\} &= 0.5943 & \leftarrow 2 \\ \Pr\{\text{TR} = 1 | V_b, V_e, V_m\} &= 0.00056469 \\ \Pr\{\text{MOSFET} = 1 | V_b, V_e, V_m\} &= 0.044391 \\ \Pr\{\text{PWM} = 1 | V_b, V_e, V_m\} &= 0.45402 \\ \Pr\{\text{bearing} = 1 | V_b, V_e, V_m\} &= 0.00049766 \\ \Pr\{\text{M.Wind.} = 1 | V_b, V_e, V_m\} &= 0.50274 & \leftarrow 3 \end{aligned}$$

Computing conditional probabilities given sensor-based fault detection

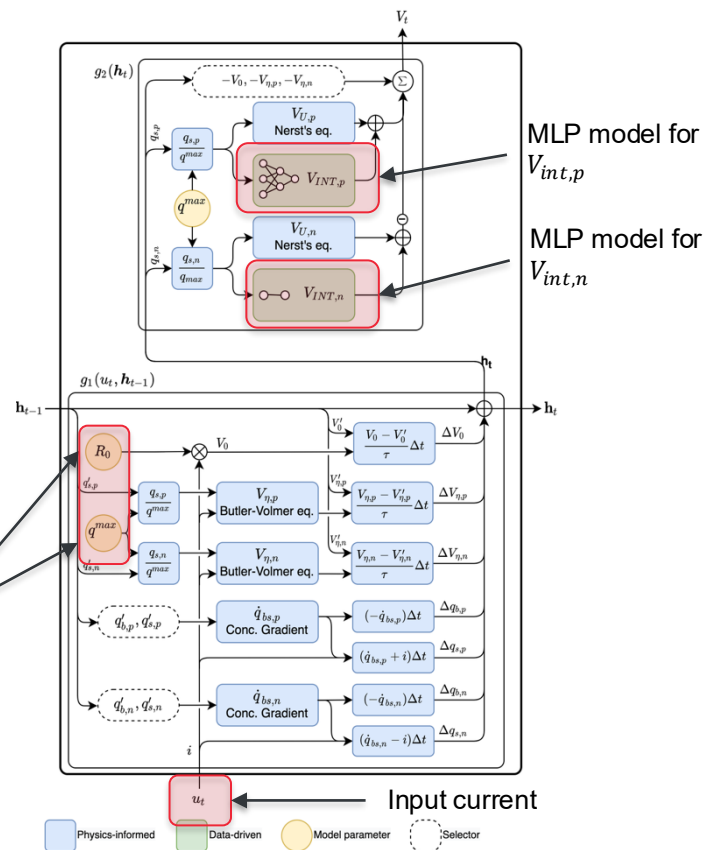
Prognostics

System input

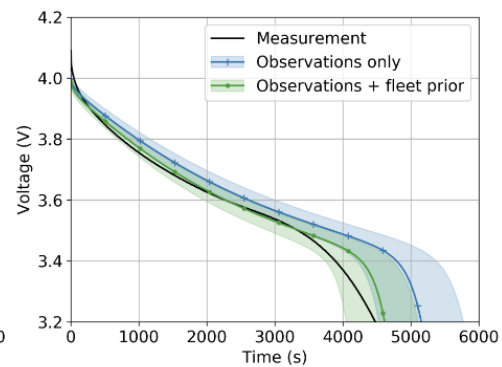
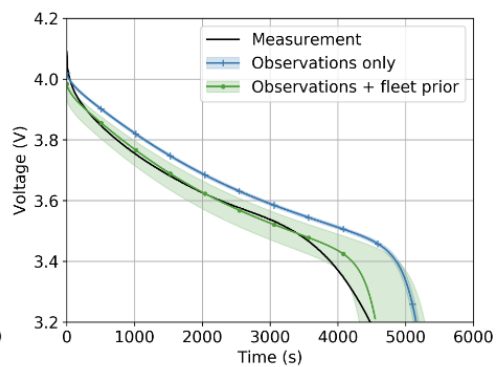
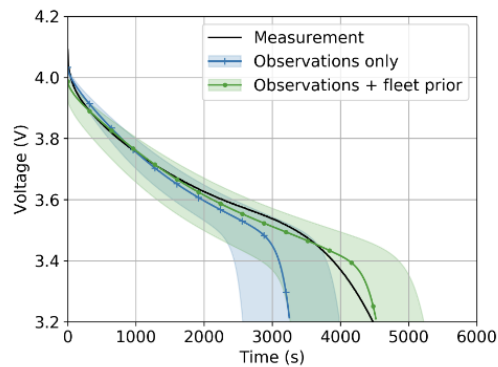


PINN's Architecture

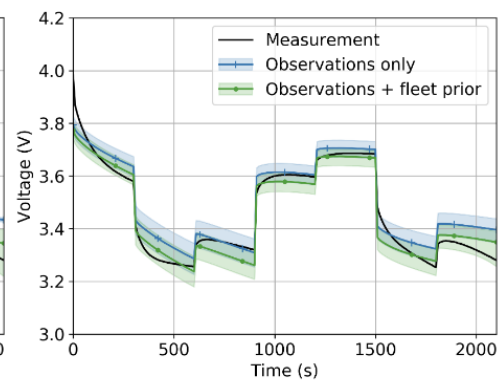
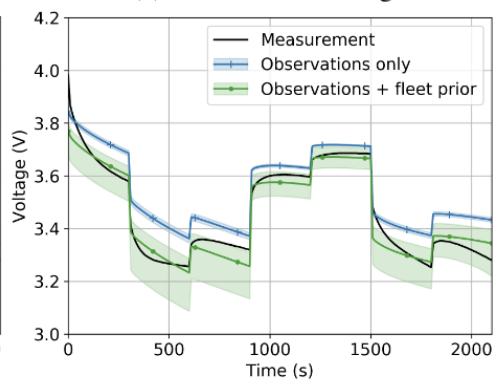
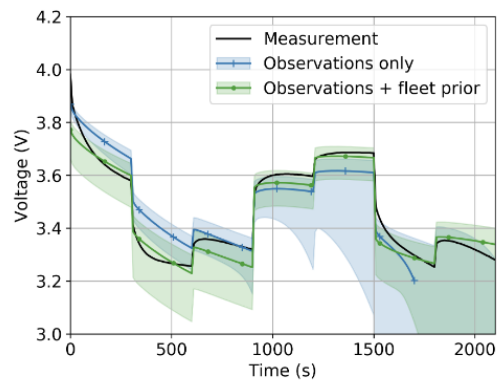
Unknown (physical) parameters



Li-ion Battery SOC estimation

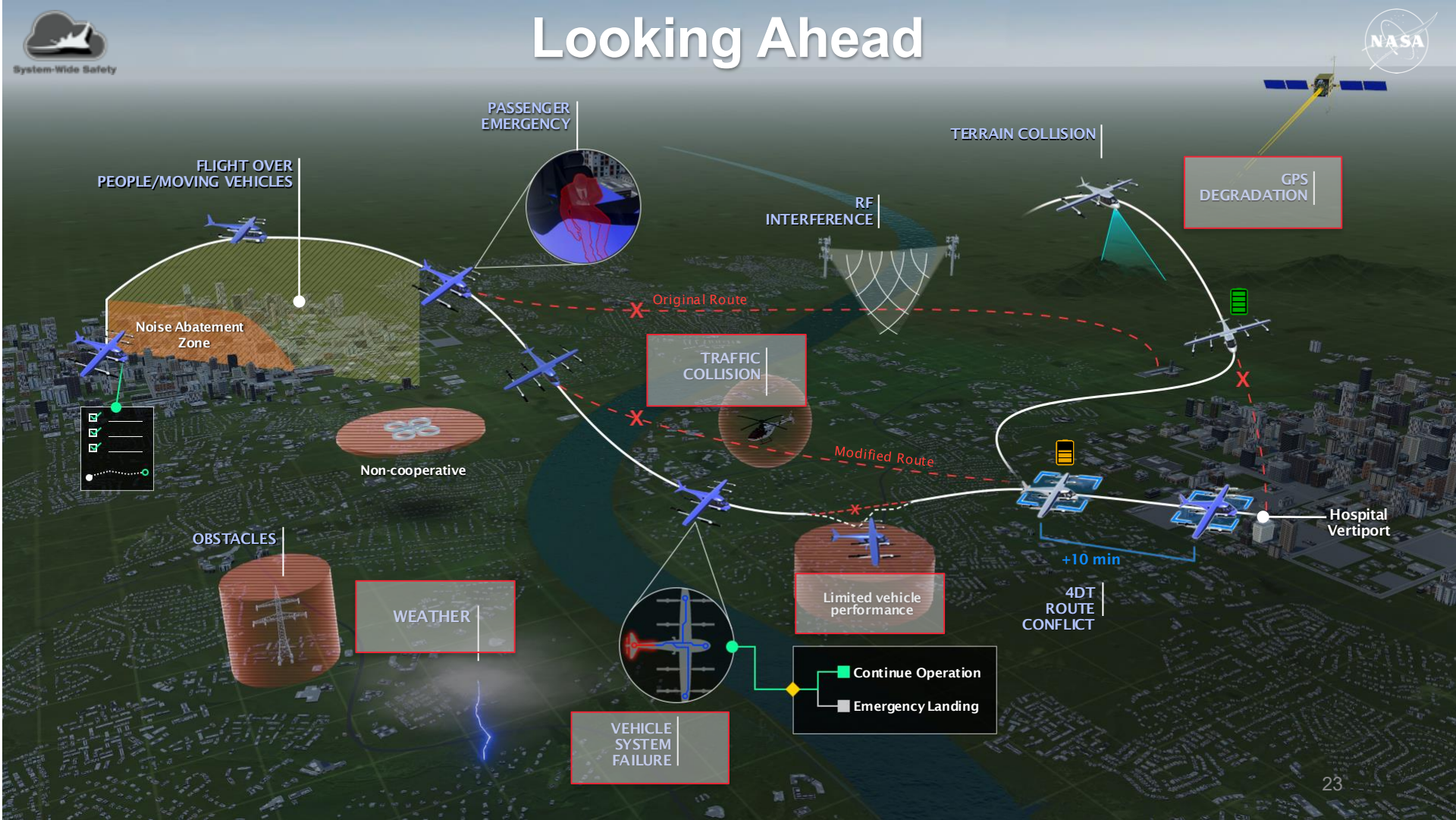


(a) Reference discharge.



(b) Random-loading discharge.

Looking Ahead



Data Repository – Open Source

<https://ti.arc.nasa.gov/tech/dash/groups/pcoe/prognostic-data-repository/>

Randomized Battery Usage Data Set

Publications using this data set

MOSFET Thermal Overstress Aging Data Set

Publications using this data set

Descr	Descript	Capacitor Electrical Stress Data Set - 2
Form	Publications using this data set	
Data	Format	Turbofan Engine Degradation Simulation Data Set-2
	Dataset	Publications using this data set
	Dataset Citation	
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Description	The generation of data-driven prognostics models requires the availability of datasets with run-to-failure trajectories. In order to contribute to the development of these methods, the dataset provides a new realistic dataset of run-to-failure trajectories for a small fleet of aircraft engines under realistic flight conditions. The damage propagation modelling used for the generation of this synthetic dataset builds on the modeling strategy from previous work . The dataset was generated with the Commercial Modular Aero-Propulsion System Simulation (C-MAPSS) dynamical model. The data set is been provided by the Prognostics CoE at NASA Ames in collaboration with ETH Zurich and PARC. Readme file for the dataset describing the experimental details and data can be found here .
Format	The dataset is in csv format and has been zipped. A python code to unzip the files can be found here .
Datasets	+ Download Turbofan Engine Degradation Simulation Data Set - 2 (8862 downloads)
Dataset Citation	M. Chao, C.Kulkarni, K. Goebel and O. Fink (2021). "Aircraft Engine Run-to-Failure Dataset under real flight conditions", NASA Ames Prognostics Data Repository (http://ti.arc.nasa.gov/project/prognostic-data-repository), NASA Ames Research Center, Moffett Field, CA



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chetan.s.kulkarni@nasa.gov