Credit: www.nasa.gov

Fault Detection, Prognostics and Decision Making Framework for Autonomous Systems

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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

*SWS Management Office

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.

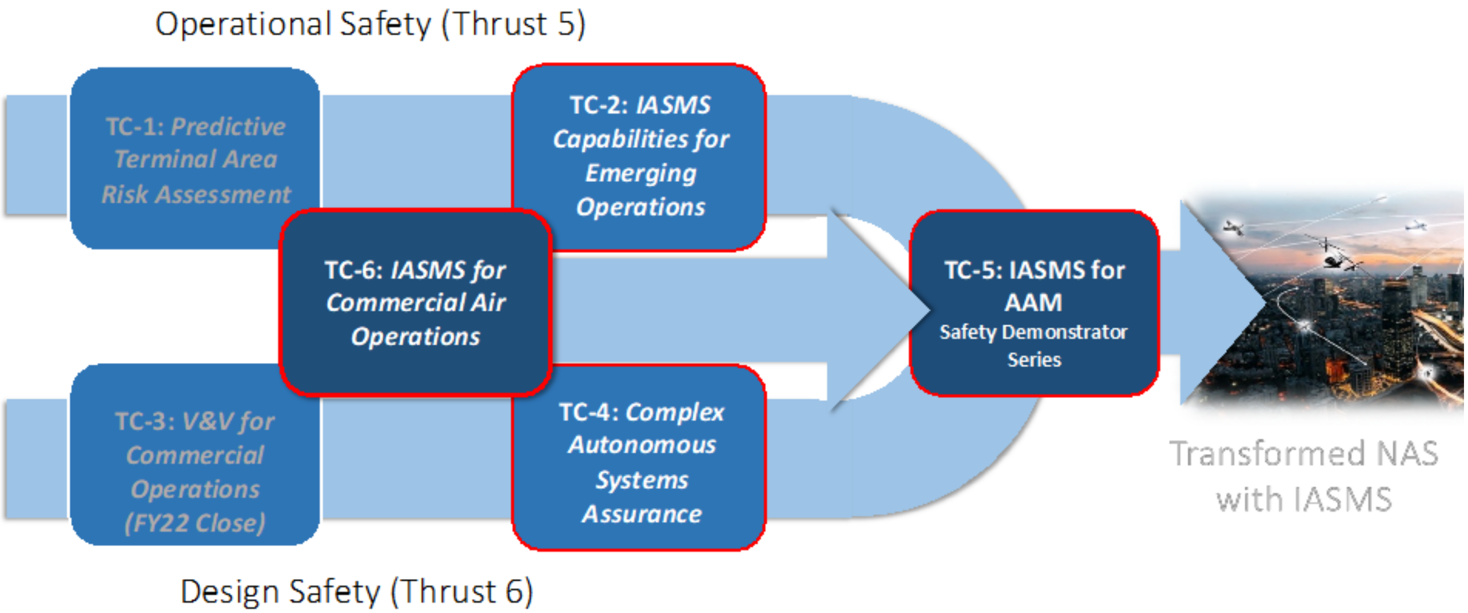
Current Technical Challenges (TCs):

- **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 Management Office

SWS Project Research Portfolio



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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

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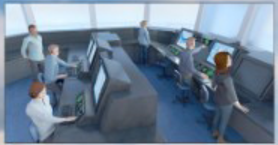
Innovating the Future of Aviation

Human-Centric Capabilities

Safety + Density
Human centered traffic &
Safety management



Digitally Transformed Infrastructure

Collaborative Environment
Service oriented
architecture
for tailored mission services
+ ML
+ IoT

Automation-Enabled Diversity

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

Evolution of Airspace Operations and Safety

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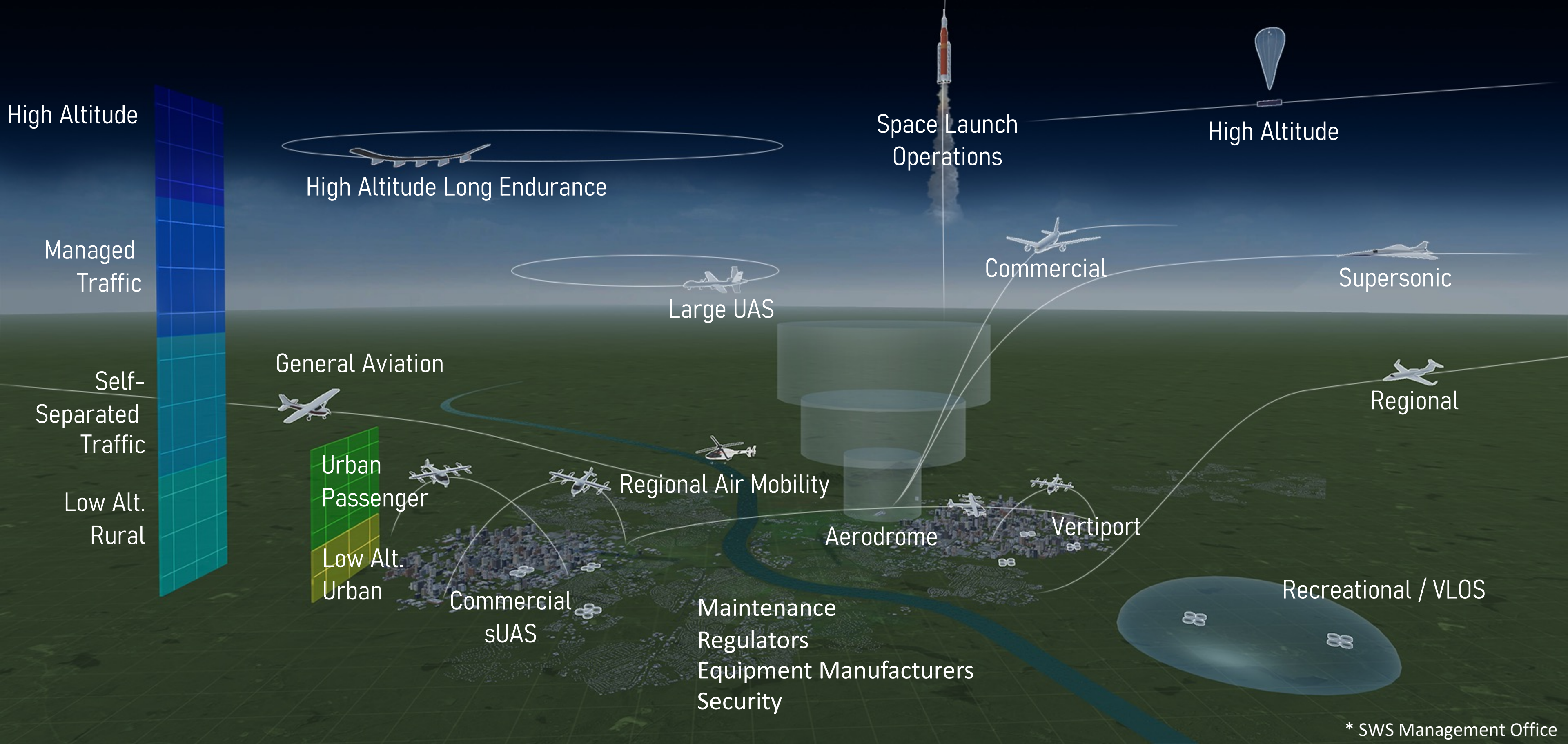
Variety of Aviation Participants



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System-Wide Safety

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**

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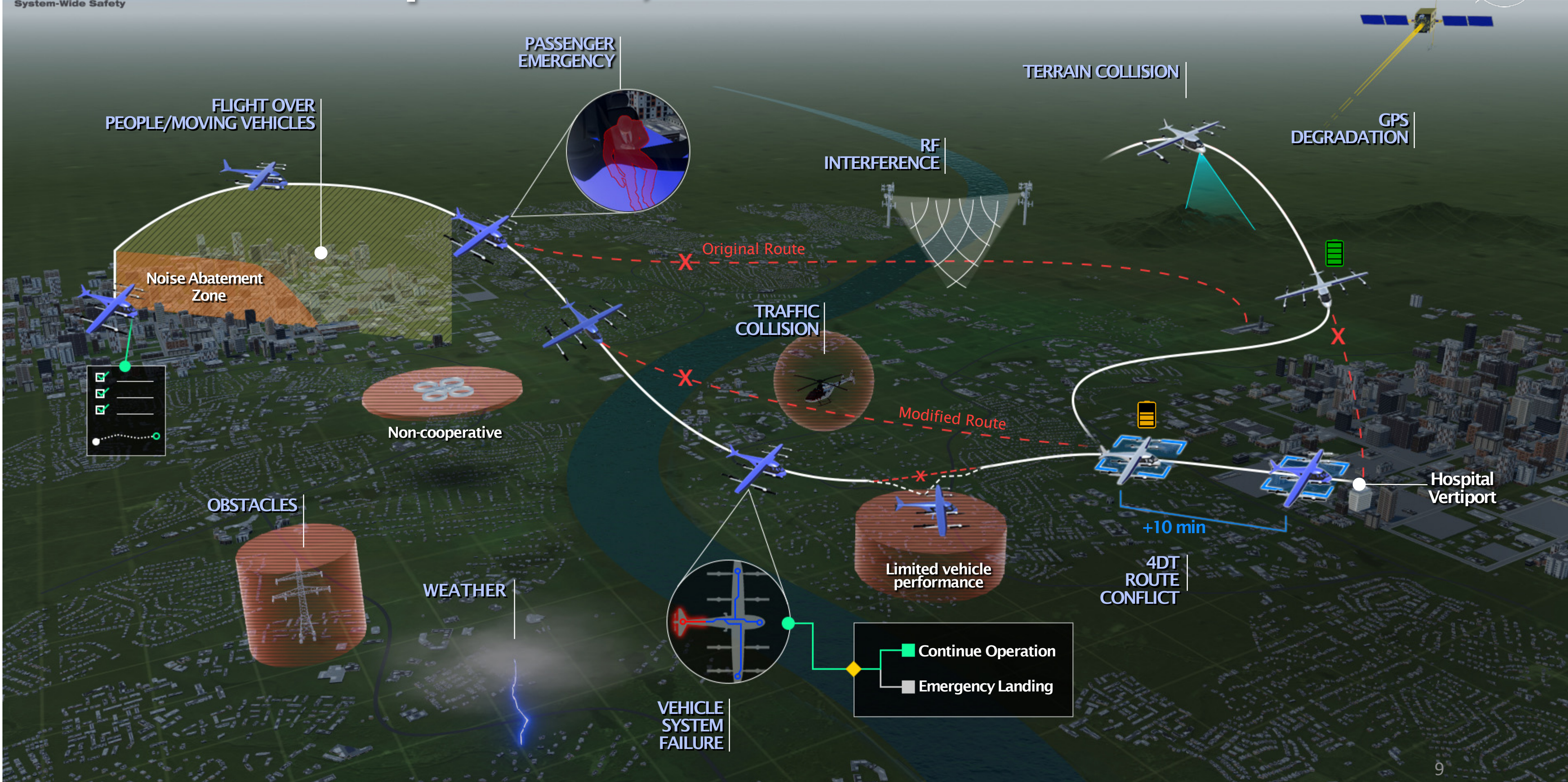
Complexities, Risks and Constraints



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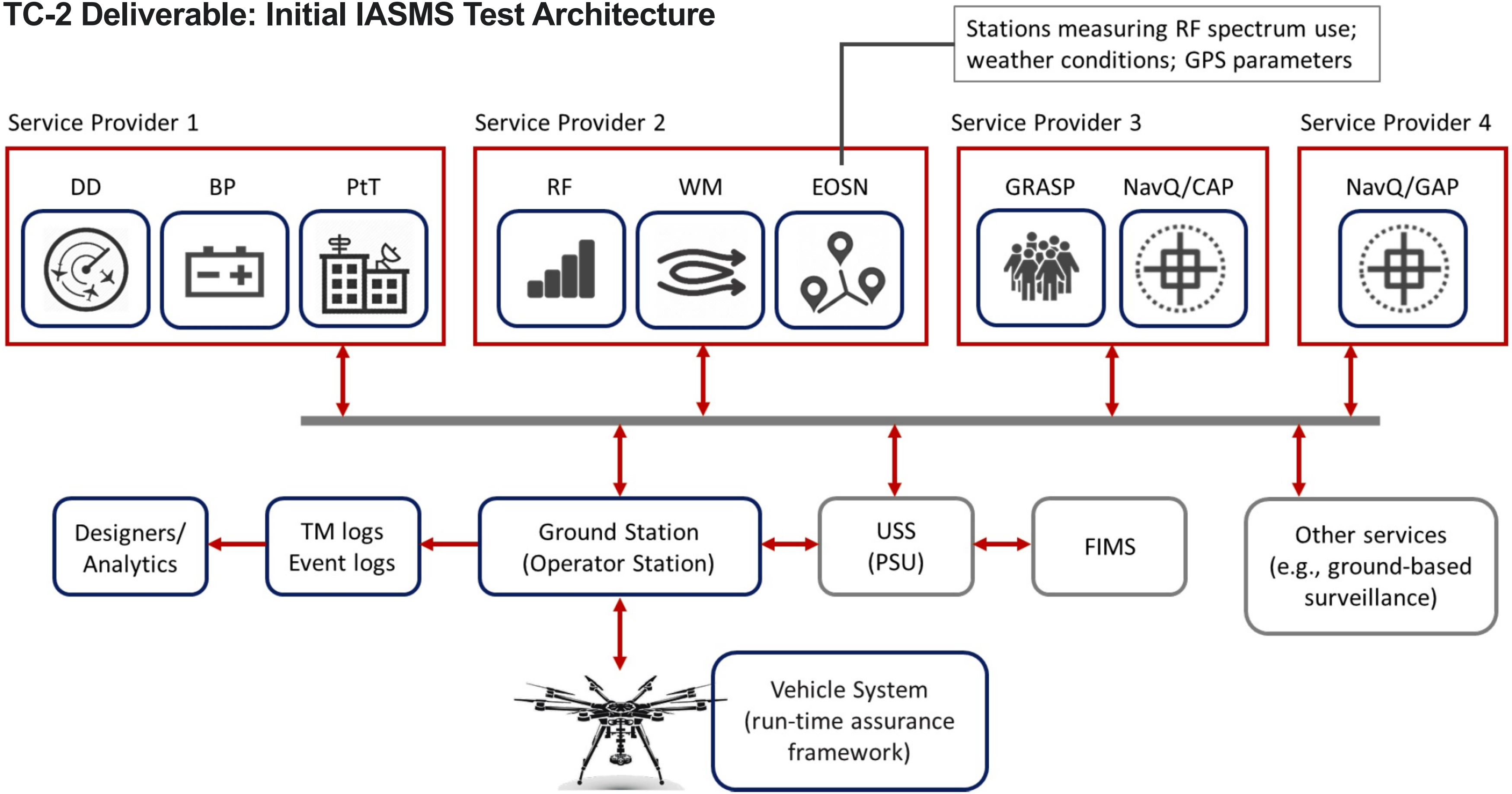
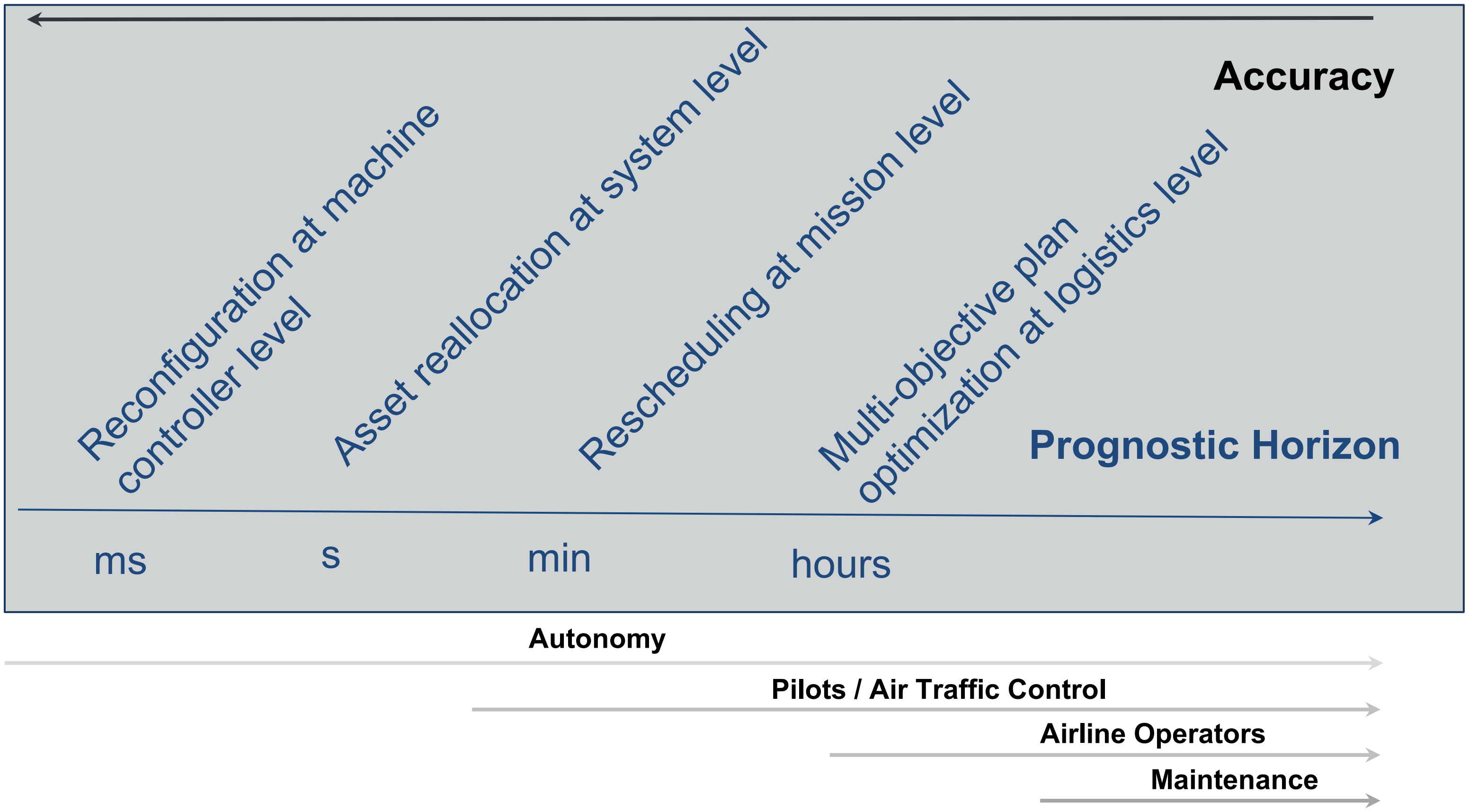
Background

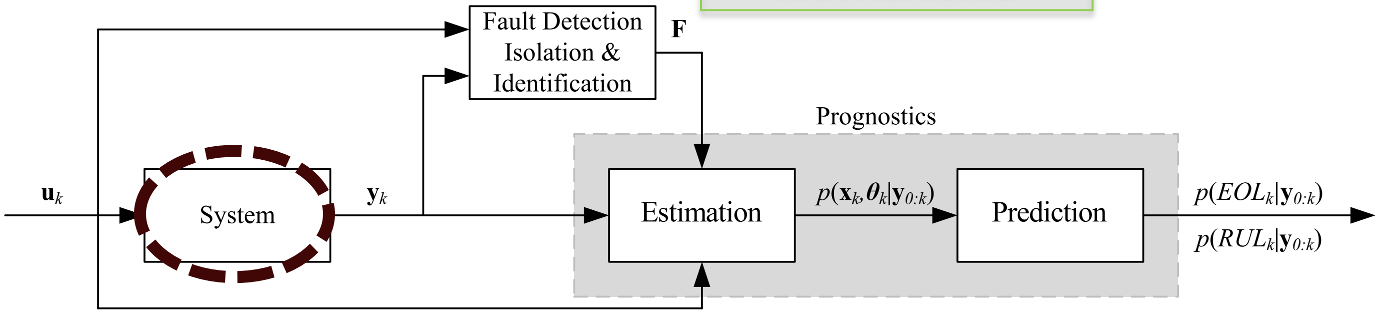
TC-2 Deliverable: Initial IASMS Test Architecture




Accuracy
Reconfiguration at machine controller level
Asset reallocation at system level
Rescheduling at mission level
Multi-objective plan optimization at logistics level
Prognostic Horizon
ms
s
min
hours
Autonomy
Pilots / Air Traffic Control
Airline Operators
Maintenance

1 System receives inputs, produces outputs

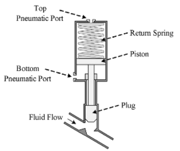
2 Identify active damage mechanisms



3 Estimate current state and parameter values

4 Predict EOL and RUL as probability distributions

- Model underlying physics of a component/subsystem

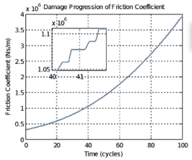


$$f_g(p_1,p_2)=\begin{cases} C_sA_sp_1\sqrt{\frac{\gamma}{ZR_gT}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}}, & p_1\geq p_2 \wedge p_1/p_2 \geq \left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} \\ C_sA_sp_1\sqrt{\frac{2}{ZR_gT}\left(\frac{\gamma}{\gamma-1}\right)\left(\left(\frac{p_2}{p_1}\right)^{2/\gamma}-\left(\frac{p_2}{p_1}\right)^{(\gamma+1)/\gamma}\right)}, & p_1\geq p_2 \wedge p_1/p_2 < \left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} \\ C_sA_sp_2\sqrt{\frac{\gamma}{ZR_gT}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}}, & p_1< p_2 \wedge p_2/p_1 \geq \left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} \\ C_sA_sp_2\sqrt{\frac{2}{ZR_gT}\left(\frac{\gamma}{\gamma-1}\right)\left(\left(\frac{p_1}{p_2}\right)^{2/\gamma}-\left(\frac{p_1}{p_2}\right)^{(\gamma+1)/\gamma}\right)}, & p_1< p_2 \wedge p_2/p_1 < \left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma-1)} \end{cases}$$

$$f_t(t)=f_g(p_t(t),u_t(t))$$
$$f_b(t)=f_g(p_b(t),u_b(t))$$

$$f_v(t)=\frac{x(t)}{L_s}C_vA_v\sqrt{\frac{2}{\rho}|p_{fl}-p_{fr}|}\mathrm{sign}(p_{fl}-p_{fr})$$

- Model physics of damage propagation mechanisms



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

- Determine criteria for End-of-Life threshold

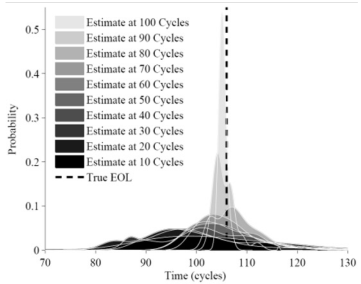
$$EOL(t_P)\triangleq\inf\{t\in\mathbb{R}:t\geq t_P\wedge T_{EOL}(\mathbf{x}(t),\boldsymbol{\theta}(t))=1\}$$

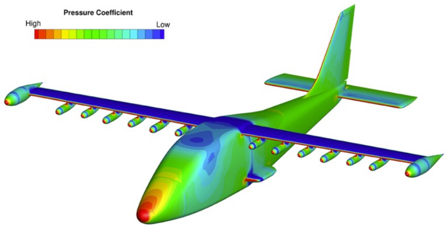
- Develop algorithms to propagate damage into future

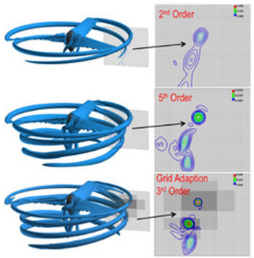
Algorithm 2 EOL Prediction

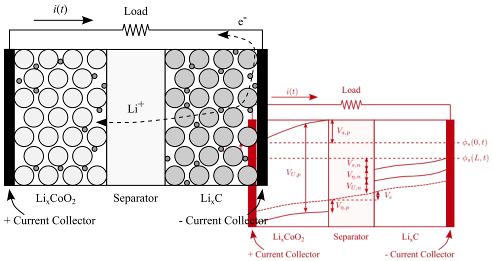
Inputs: $\{(\mathbf{x}^i_{k_P},\boldsymbol{\theta}^i_k),w^i_{k_P}\}^N_{i=1}$
Outputs: $\{EOL^i_{k_P},w^i_{k_P}\}^N_{i=1}$
for $i=1$ **to** N **do**
  $k\leftarrow k_P$
  $\mathbf{x}^i_k\leftarrow\mathbf{x}^i_{k_P}$
  $\boldsymbol{\theta}^i_k\leftarrow\boldsymbol{\theta}^i_{k_P}$
  while $C_{EOL}(\mathbf{x}^i_k,\boldsymbol{\theta}^i_k)=0$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

- Deal with uncertainty

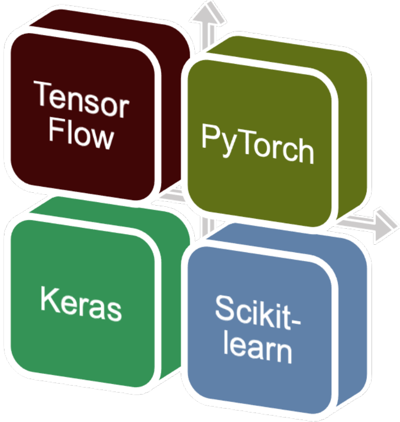




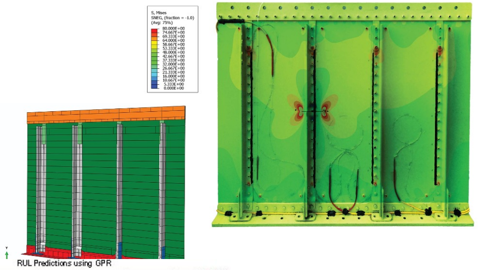


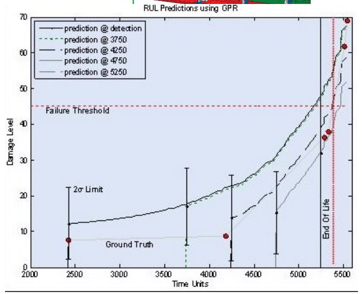


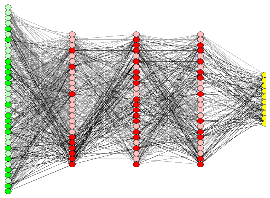
Machine-Learning underlying physics parameters



Understanding and Learning underlying Physics for Complex Systems

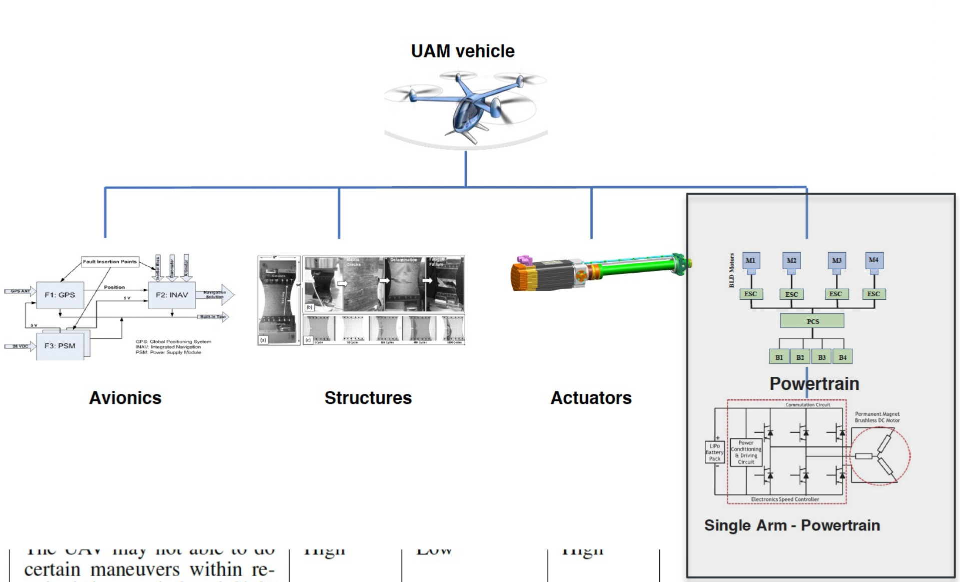


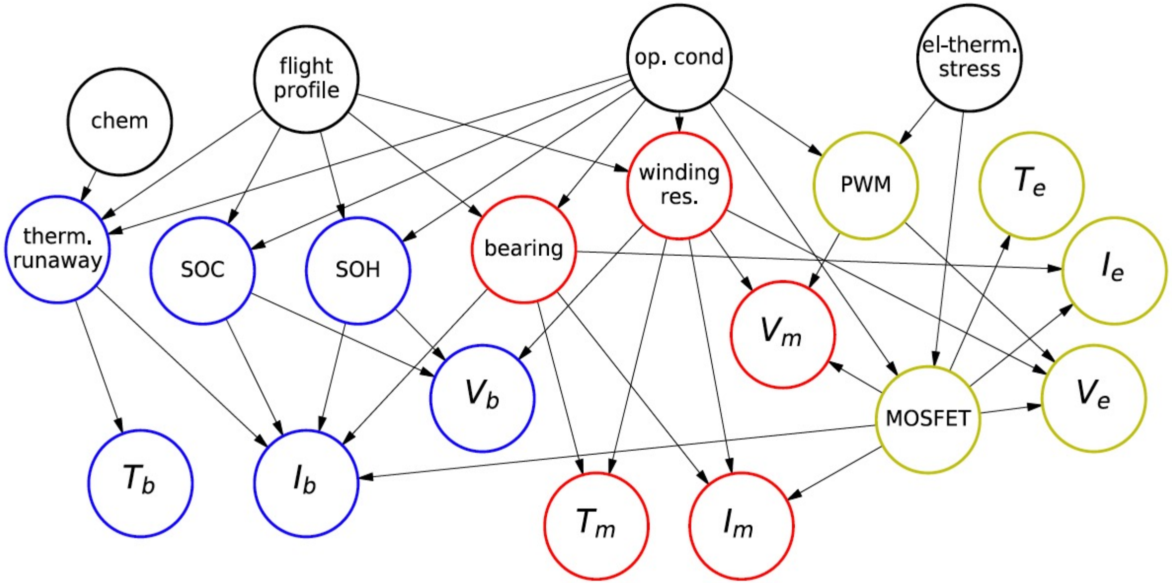


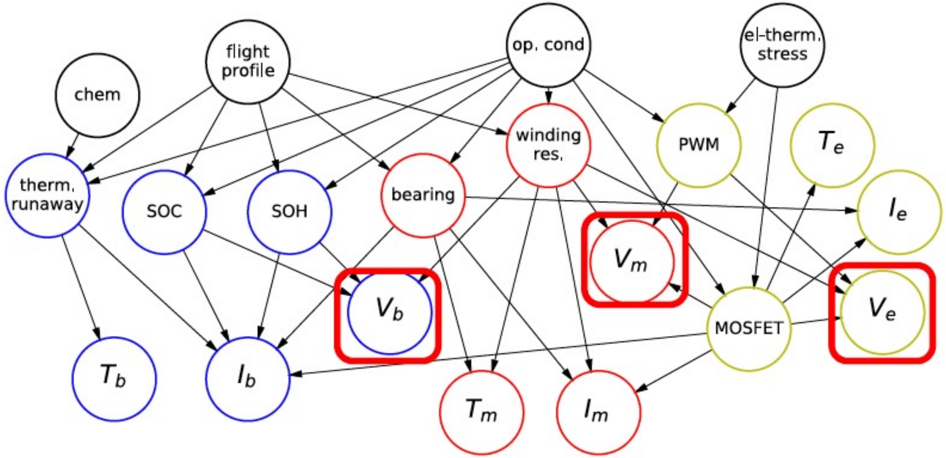


Diagnostics

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 batterie may not directly affec 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 batterie may not directly affec other systems				
Motor (Single)	Power Consumption	change in winding resistance, bearing faults	High draw currents decrease the battery RUI shortening flight tim considerably				
Motor (Multiple)	Power Consumption, Low insulation resistance, bearings	change in winding resistance, bearing faults	High draw currents decrease the battery RUI shortening flight tim considerably				
ESC (Single)	Power Consumption	operational stress, High electrical, thermal stress on the components	Change in switchin frequency, MOSFE degradation, stucl faults				
ESC (Multiple)	Power Consumption	operational stress, High electrical, thermal stress on the components	Change in switchin frequency, MOSFE degradation, stucl faults				
CES	Filtering Capacitor/MOSFET failures	Operational stress, High electrical, thermal stress on the components	Directly affects operation of the power train system	UAV may not able to do certain maneuvers within required time period and flight profile	High	Low	High




chem
flight profile
op. cond
el-therm. stress
therm. runaway
SOC
SOH
bearing
winding res.
PWM
MOSFET
T_e
I_e
V_e
V_m
V_b
T_b
I_b
T_m
I_m



Anomalous voltages readings

$V_b = V_e = V_m = 1$

$$\Pr\{\mathrm{SOC} = 1 | V_b, V_e, V_m\} = 0.82021 \quad \overset{1}{\leftarrow}$$

$$\Pr\{\mathrm{SOH} = 1 | V_b, V_e, V_m\} = 0.5943 \quad \overset{2}{\leftarrow}$$

$$\Pr\{\mathrm{TR} = 1 | V_b, V_e, V_m\} = 0.00056469$$

$$\Pr\{\mathrm{MOSFET} = 1 | V_b, V_e, V_m\} = 0.044391$$

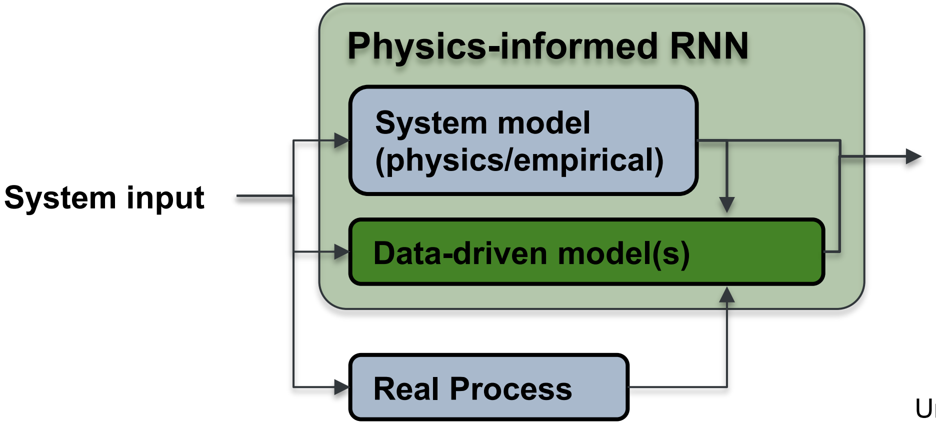
$$\Pr\{\mathrm{PWM} = 1 | V_b, V_e, V_m\} = 0.45402$$

$$\Pr\{\mathrm{bearing} = 1 | V_b, V_e, V_m\} = 0.00049766$$

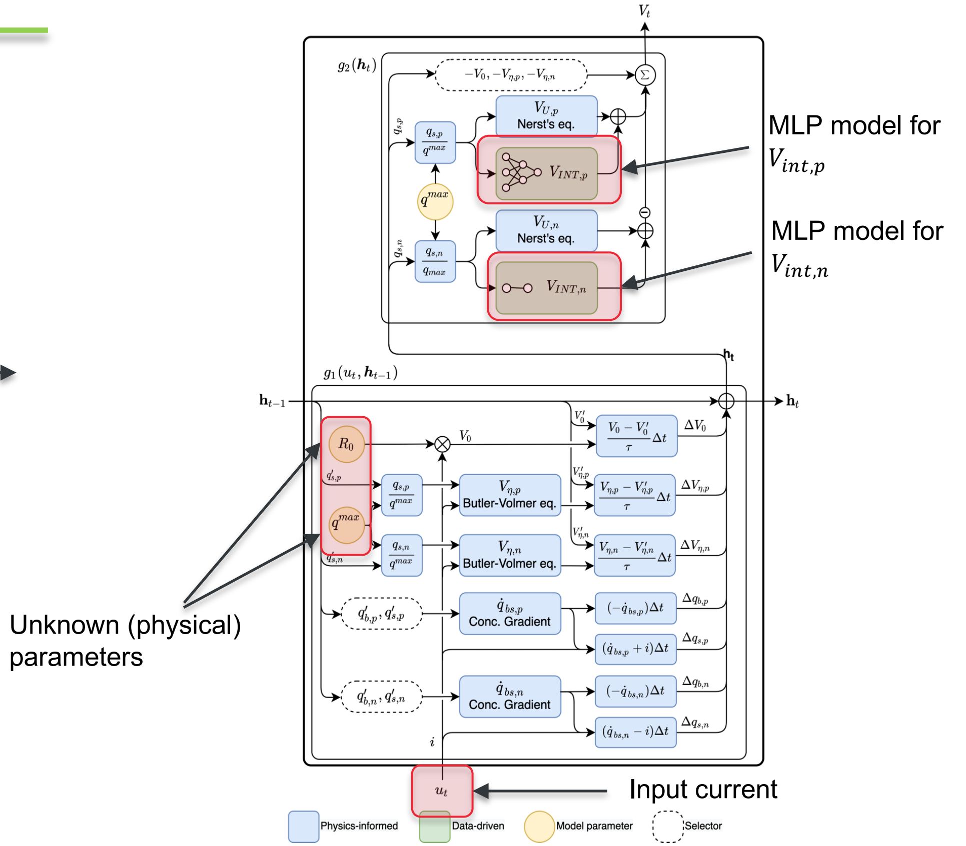
$$\Pr\{\mathrm{M.Wind.} = 1 | V_b, V_e, V_m\} = 0.50274 \quad \overset{3}{\leftarrow}$$

Computing conditional probabilities given sensor-based fault detection

Prognostics

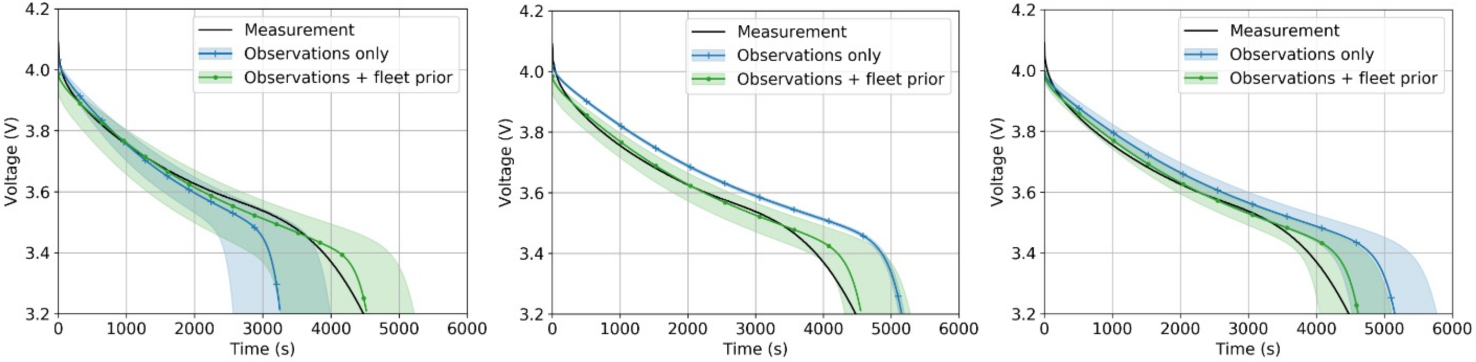


PINN’s Architecture

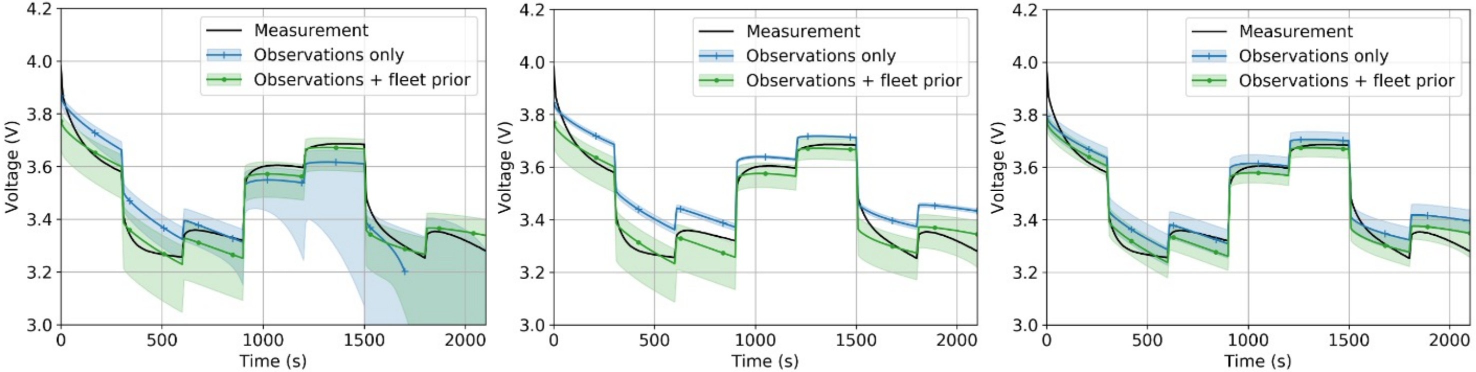


Li-ion Battery SOC estimation

*MLP – Multi layer Perception

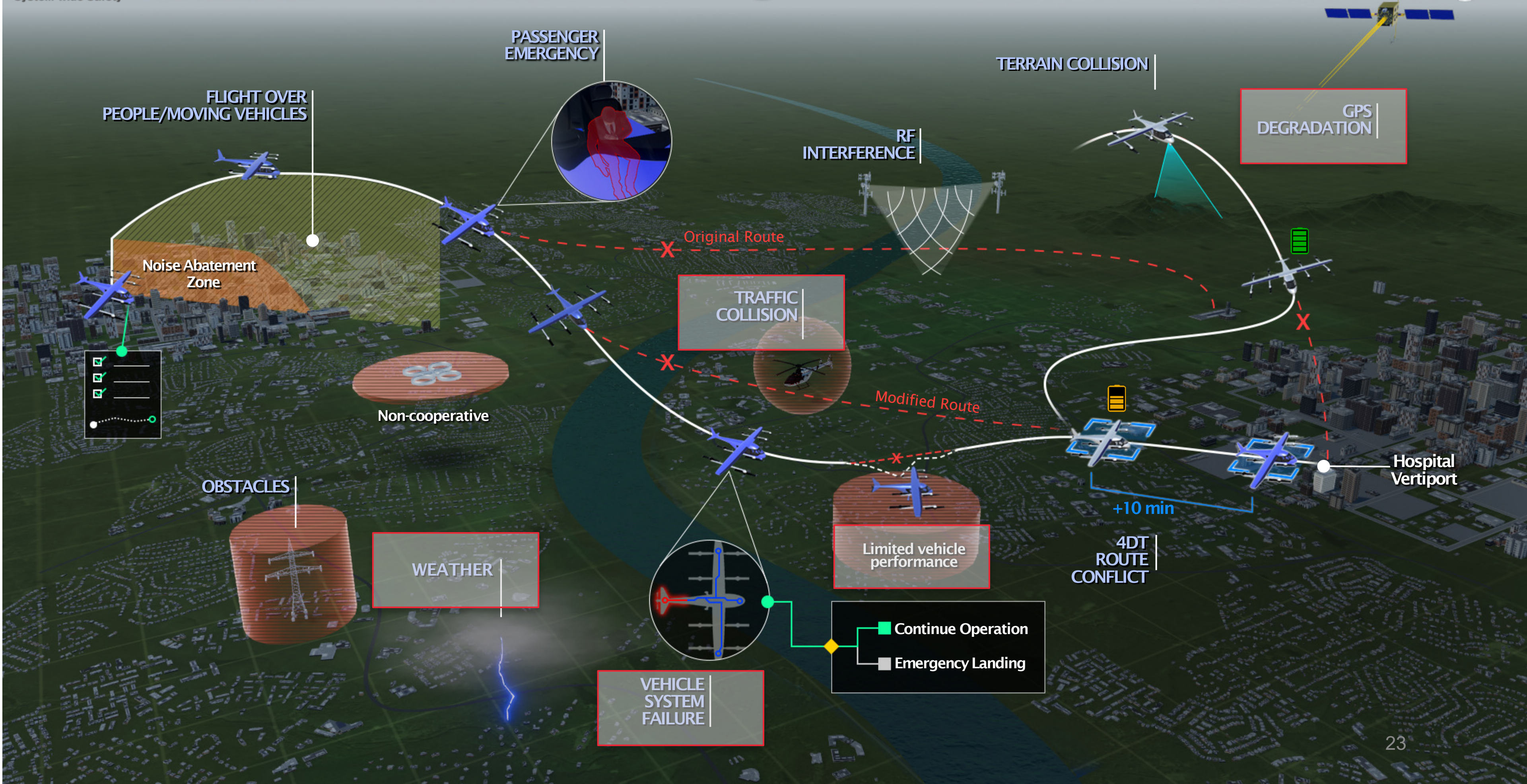


(a) Reference discharge.



(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

Capacitor Electrical Stress Data Set - 2

Turbofan Engine Degradation Simulation Data Set-2
Publications using this data set

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 experimetal 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

Credit: www.nasa.gov

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