IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

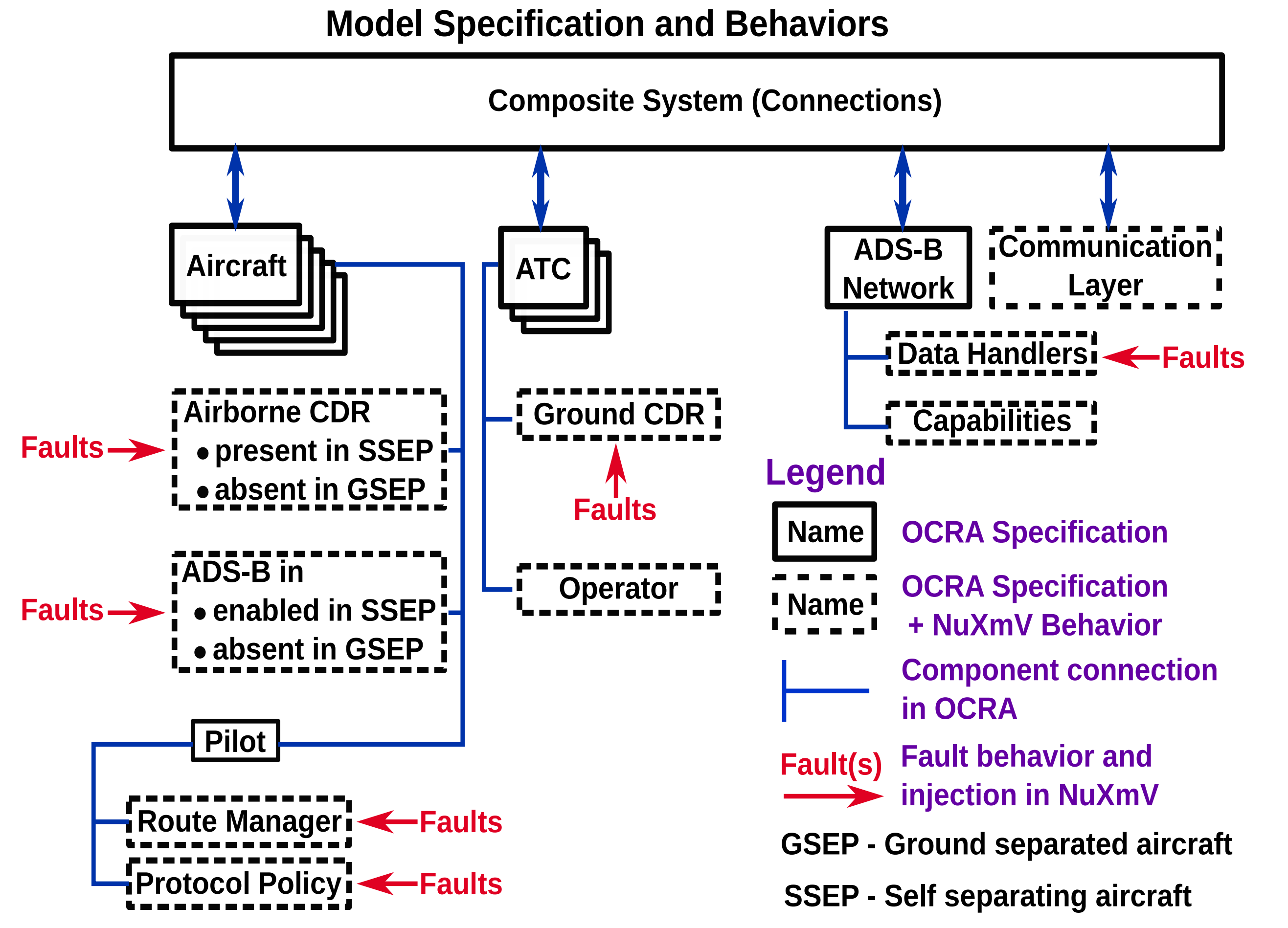
CAREER: Theoretical Foundations of the UAS in the NAS Problem (Unmanned Aerial Systems in the National Air Space)

PI: Kristin Yvonne Rozier

In order to address the UAS in the NAS problem, we must take a holistic view, integrating advances in the state of the art from three intertwined perspectives: from on-board the UAS, from the environment (NAS), and from the underlying theory enabling their formal analysis.

UAS in the NAS from the NAS Perspective

- Comparative symbolic analysis of designs
- Modeling for UAS-specific designs
- Specializing formal tools for aerospace analysis

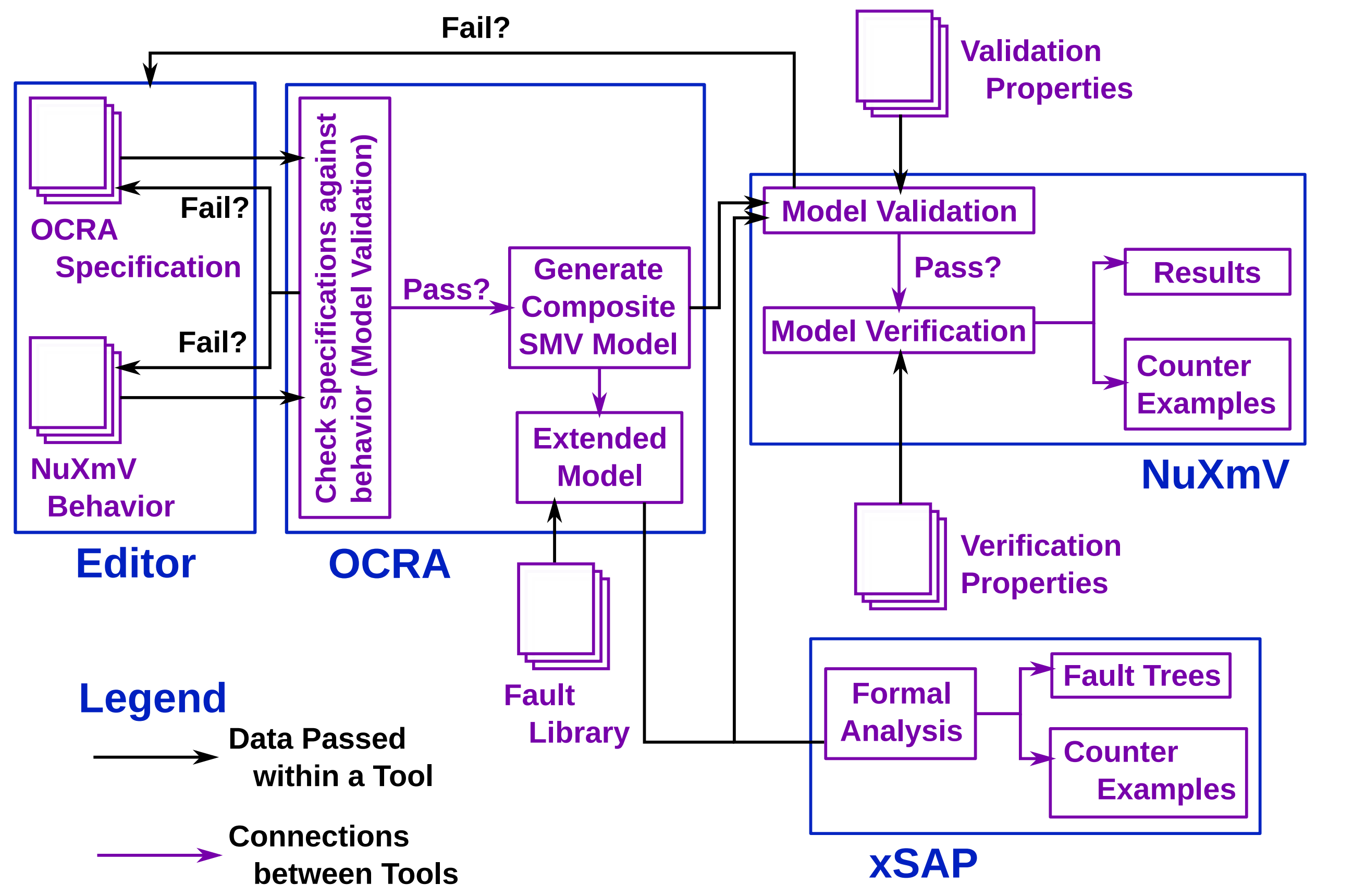


Model Specification and Behaviors

GSEP - Ground separated aircraft

SSEP - Self separating aircraft

Plan for compositional modeling of the design space for NASA's set of NextGen automated air traffic control architectures. The models will combine symbolic model checking and contract-based design techniques to address scalability challenges and enable us to effectively represent and reason comparatively about the full-scale designs.



Modeling and analysis pipeline using the nuXmv tool suite. New PANDA encodings will be encode validation and verification specifications to advance the state of the art as measured by efficiency and scalability. Later work will include algorithmic advancesto the areas covered by OCRA and xSAP to enablescalable analysis of real-life designs.

Laboratory for Temporal Logic

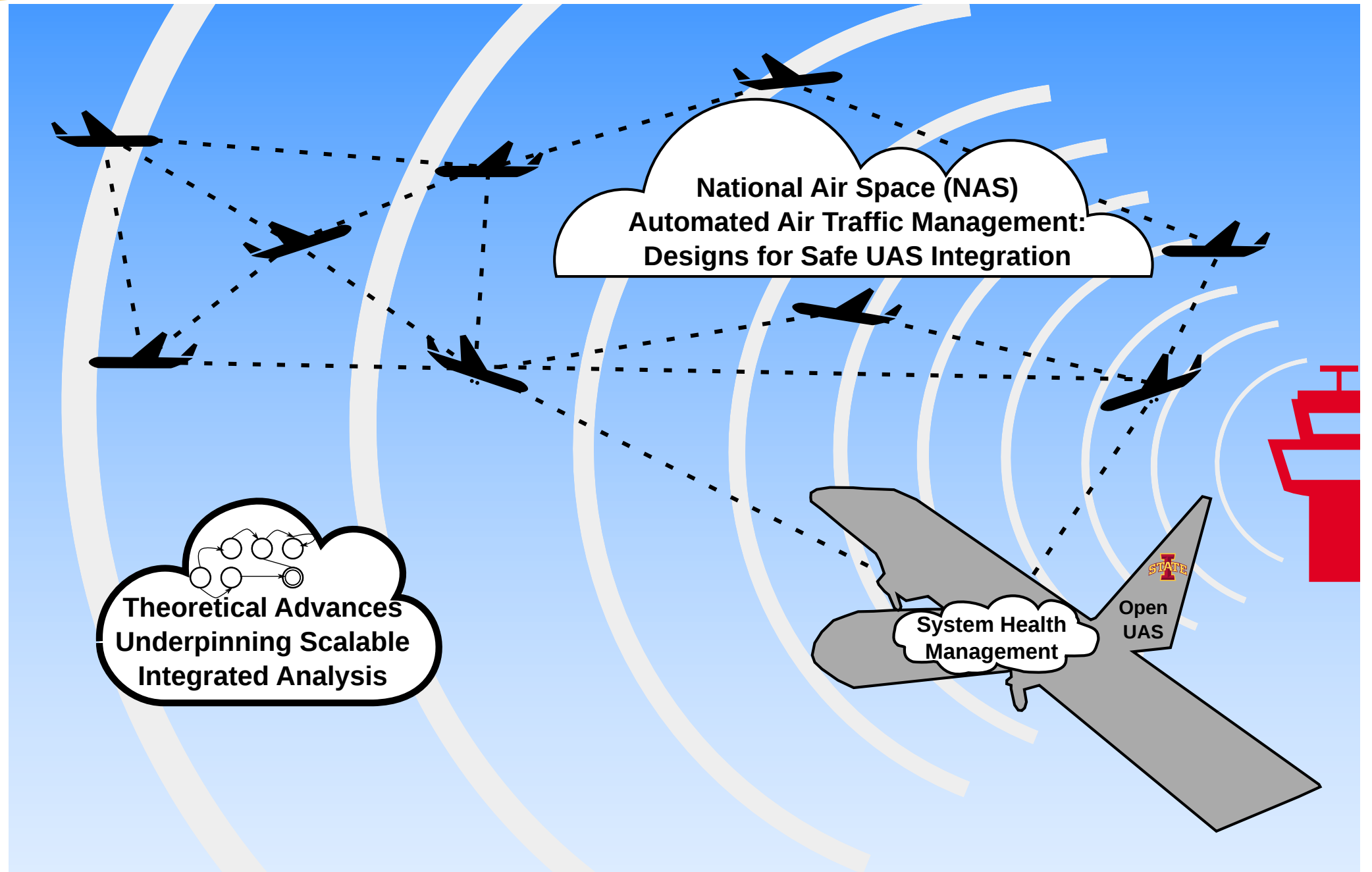


Figure 1: Overview of CAREER trajectory, a holistic view of the UAS in the NAS problem in three integrated thrusts: advancingon-board UAS capabilities, fleet-level reasoning, and theoreticalunderpinnings needed to advance the state of the art for the broader problem of UAS in the NAS. Research is facilitated by an educational open UAS design.

Overview

Due to increasing use by civil and federal authorities and vast commercial and amateur applications, Unmanned Aerial Systems (UAS) will be introduced into the National Air Space (NAS); the question is only how we can do this safely. NASA and the FAA are designing a new automated air traffic control system (NextGen) for all aircraft, manned or unmanned. New algorithms and tools need to be developed to enable computation of the complex questions inherent in designing such a system while proving adherence to rigorous safety standards. We must grow the tools of formal analysis to be able to address the UAS in the NAS problem, reason about UAS integration during the design phase of NextGen, and tie this design to on-board capabilities to provide runtime System Health Management (SHM), ensuring the safety of people and property. To address the UAS in the NAS problem, we take a holistic view, integrating advances in the state of the art from three intertwined perspectives: on-board the UAS, the environment (NAS), and the underlying theory enabling their formal analysis. Despite advances in formal methods, few are grounded in real-world avionics systems. There has been rapid development of UAS technologies yet few of them are formally mathematically rigorous to the degree needed for FAA safety-critical system certification. This CAREER proposal bridges that gap, integrating new UAS and air traffic control designs with advances in formal analysis. In the wealth of promising directions for autonomous UAS capabilities, this CAREER proposal fills a unique need, providing a direct synergy between on-board UAS SHM, the NAS environment in which they operate, and the theoretical foundations common to both of these.

Intellectual Merit

From the perspective of the NAS environment, this CAREER proposal will conduct a comparative analysis of NASA's designs for an automated NAS, model cutting-edge ideas for UAS integration, and address questions of scalability to include the relevant details of NextGen architectures via exploring options such as compositional verification, contract-based design, and new encodings of the system specifications. This includes new modeling algorithms and tools to enable analysis of the safety of UAS integration into the NAS, taking into account relationships with other aircraft, communications, and air traffic control. Advances from the UAS and the NAS perspectives will require theoretical research into scalable model checking and debugging of safety properties. Safety properties express the sentiment that "something bad does not happen" during any system execution; they represent the vast majority of the requirements for NextGen designs and all requirements we can monitor on-board a UAS for system heath management during runtime. From the UAS perspective, this CAREER proposal will develop new capabilities for runtime SHM that complies with current and expected future FAA regulations for UAS with a focus on increasing scalability, automation, and industrial utility over the current state of the art. Specification patterning and synthesis from physical UAS platforms will be essential for enabling real-world implementation of any SHM platform; this research will tackle these new frontiers in embedding health management capabilities on-board UAS.

Broader Impact

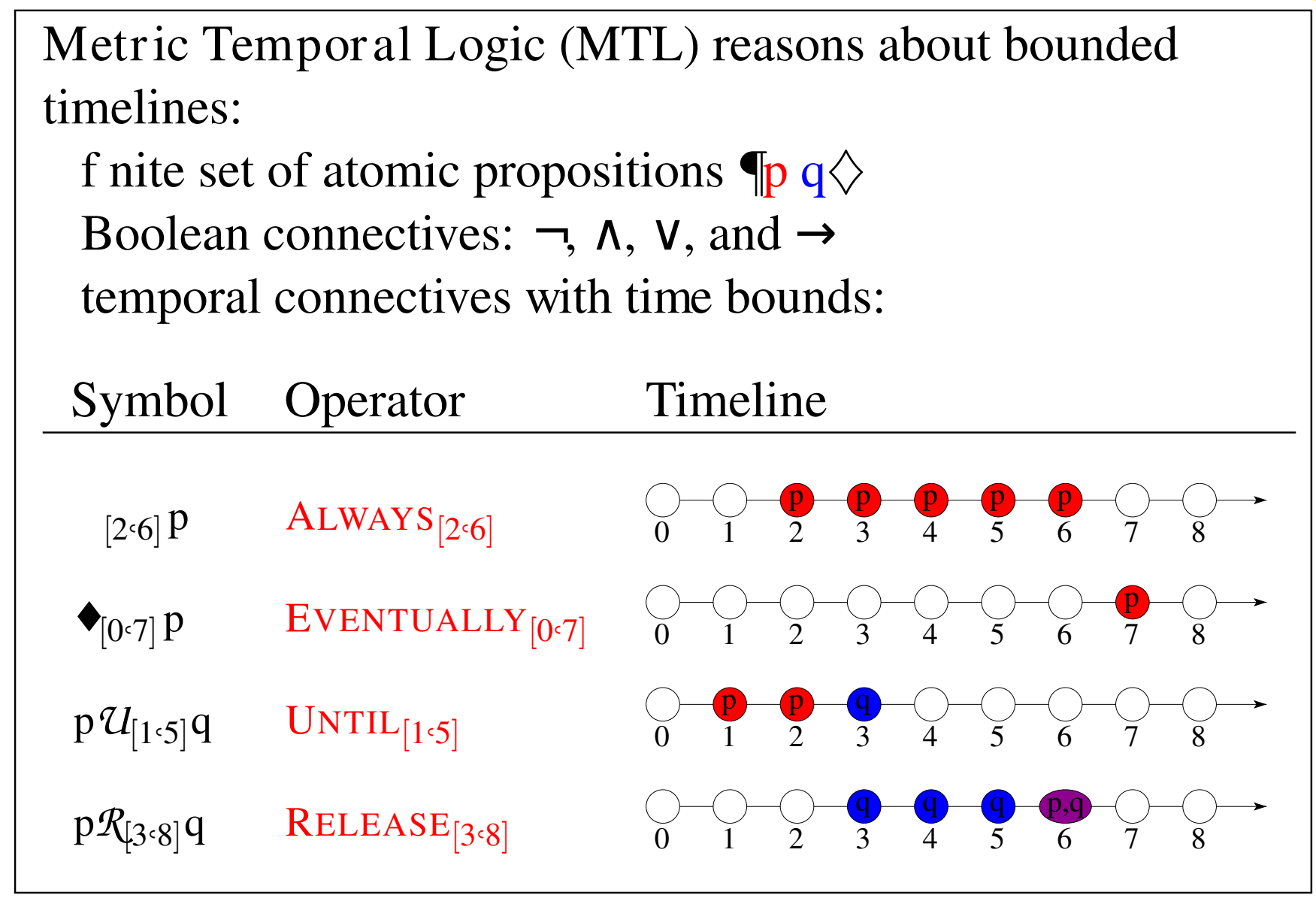
This work will help to build a safer NAS with increased capacity for UAS and create critical capabilities for SHM on-board UAS. Collaborations with aerospace system designers at NASA and tool designers at FBK will aid real-life utility and technology transfer. Current small UAS platforms are difficult to re-configure for missions requiring different sensor suites, have payload capacities that are too oddly shaped and cramped to facilitate the instrumentation required for real-time SHM, restrict internal airflow in a way that causes overheating, have battery lives that are too short to enable rigorous experimental field evaluation in complex environments, and are too restricted or expensive for use in academic environments. Broader impact will be achieved by involving undergraduate students in the design of an open-source, affordable, all-COTS and 3D-printable UAS, which will facilitate flight testing of this proposal's research advances. An open-UAS design for academia will be useful both for classroom demonstrations and as a research platform. Further impact will be achieved by using this UAS and the research it enables in interactive teaching experiences for K-12, undergraduate, and graduate students and in mentoring outreach specifically targeted at girls achieving in STEM subjects.

Publications

[1] Marco Gario, Alessandro Cimatti, Cristian Mattarei, Stefano Tonetta, and Kristin Yvonne Rozier. ``Model Checking at Scale: Automated Air Traffic Control Design Space Exploration.'' In *Proceedings of the 28th International Conference on Computer Aided Verification (CAV)*, Springer-Verlag, Toronto, Ontario, Canada, July 17-23, 2016. (acceptance rate <27%; received the ``Artifact Evaluated Stamp'' (highest mark from Artifact Evaluation Review Committee: http://barghouthi.github.io/cav16-aec/); CORE A*-ranked conference)

[2] Kristin Yvonne Rozier. ``Specification: The Biggest Bottleneck in Formal Methods and Autonomy.'' In *Proceedings of the 8th Working Conference on Verified Software: Theories, Tools, and Experiments (VSTTE)*, Toronto, Canada, July 17--18, 2016. (Invited)

[3] Rohit Dureja and Kristin Yvonne Rozier. "Combinatorial Model Checking Reduction." (under submission)



Metric Temporal Logic (MTL) reasons about bounded timelines:

f nite set of atomic propositions ¶p q◇

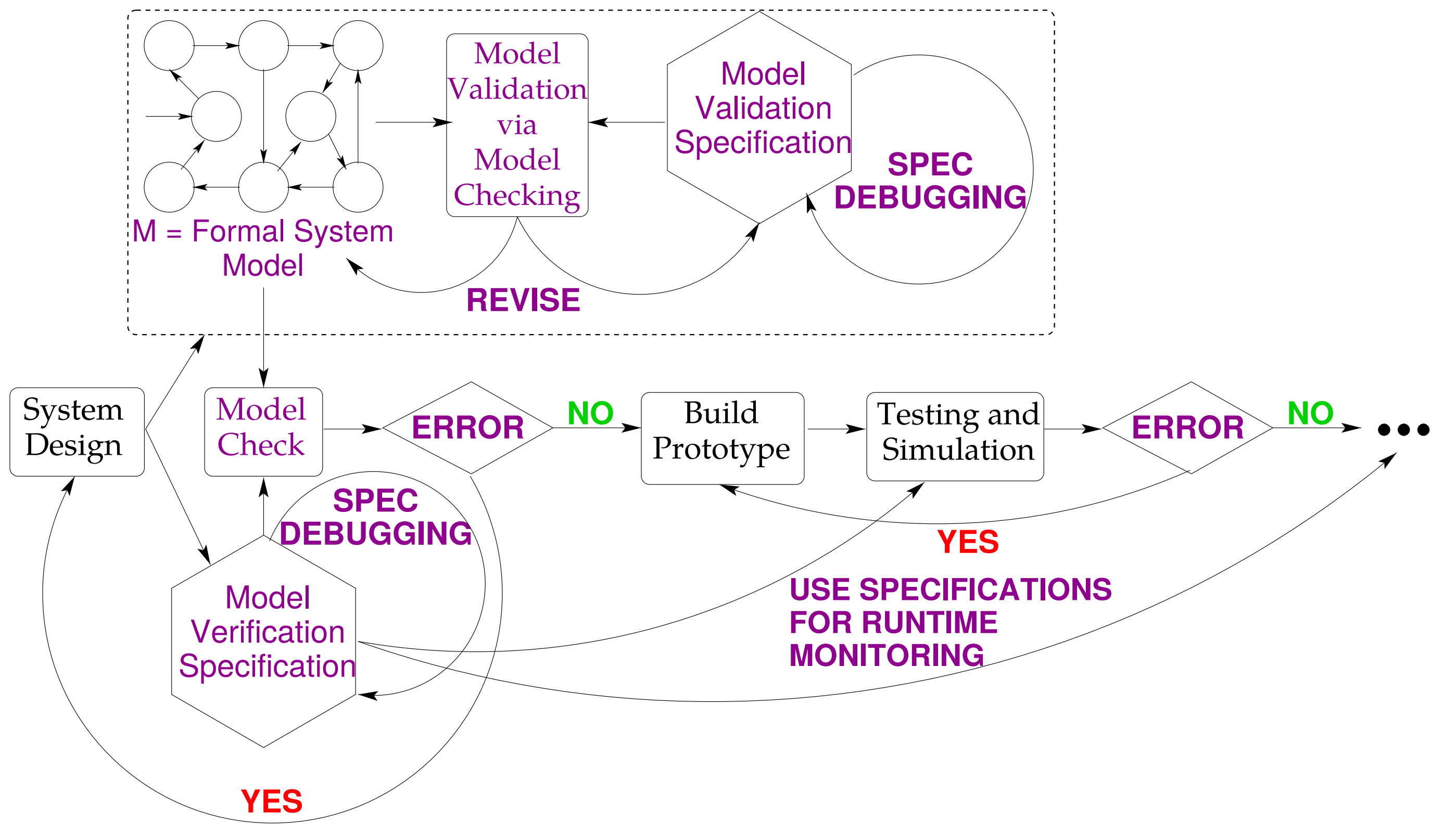
Boolean connectives: ¬, ∧, ∨, and →

temporal connectives with time bounds:

Symbol	Operator	Timeline
[2‹6] p	ALWAYS[2‹6]	
♦[0‹7] p	EVENTUALLY[0‹7]	
p𝒰[1‹5]q	UNTIL[1‹5]	
pℛ[3‹8]q	RELEASE[3‹8]	

Theoretical Advancements for Safety Property Checking

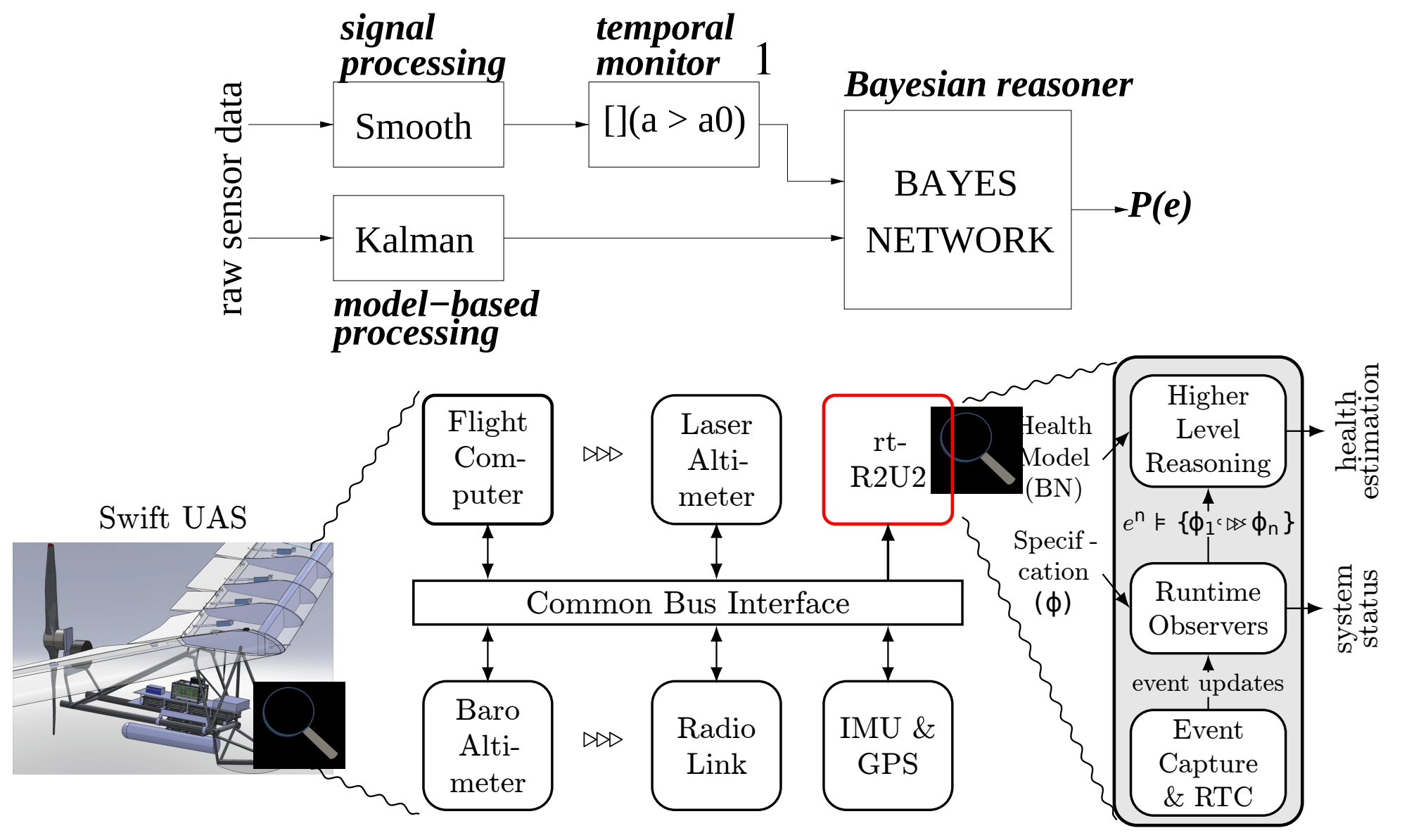
- Improving symbolic model checking via requirements encoding
- Improving explicit model checking via symbolic requirements encoding
- Evaluate both explicit and symbolic satisfiability checking via model checking



A better critical system design process, where the system design is verified previous to, and separately from, the system prototype and later implementation.

UAS in the NAS from the UAS Perspective

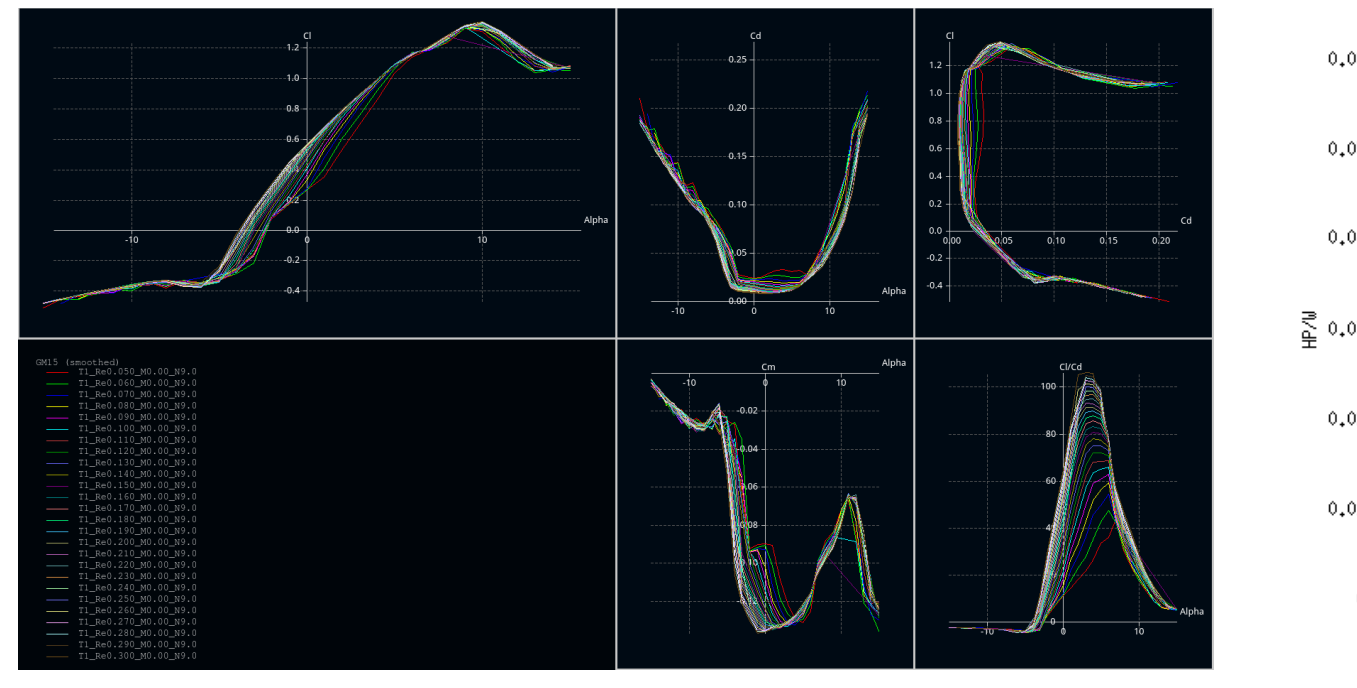
- Design for Runtime System Health Management (SHM)
- UAS specification patterns
- Synthesis of runtime requirements

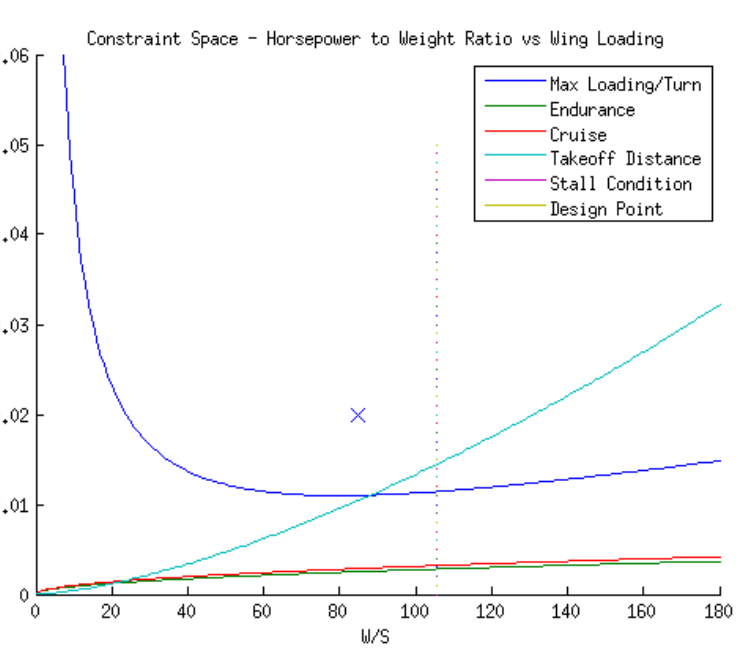


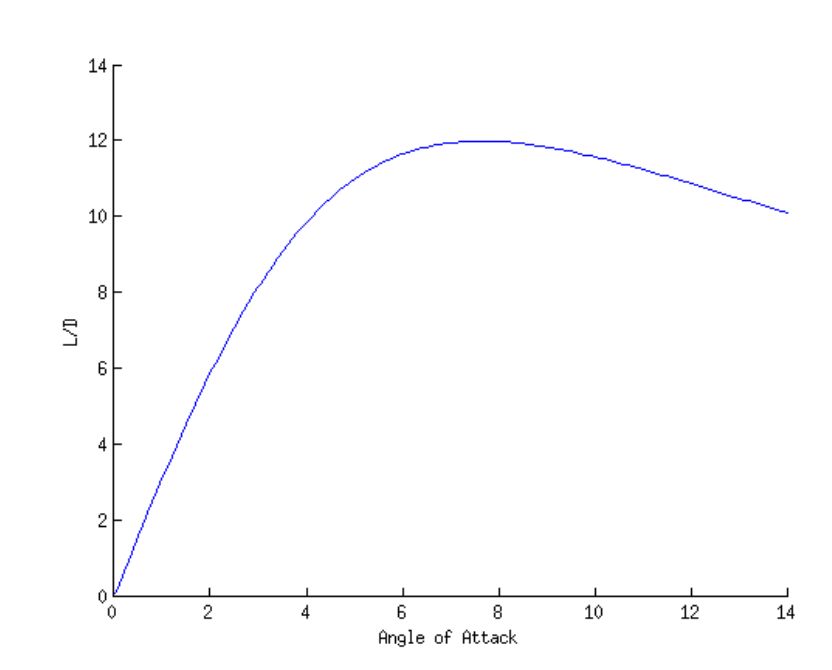
The on-board, real-time **R**ealizable, **R**esponsive, and **U**nobtrusive **U**nit (**R2U2**) provides SHM capabilities for a UAS in a certifiable way that complies with FAA regulations.

CAREER Development Plan: Education

- An Open-Source, 3D-printable Academic UAS Design
- Interactive Interdisciplinary Education
- Mentoring Girls Achieving in Non-Traditional Subjects







Max Load/Turn:

$$\frac{HP}{W} = \frac{1}{550\eta_p}\left[\frac{1}{2}\rho V^3 C_{D_O}\left(\frac{S}{W}\right) + 2K\frac{n^2}{\rho V}\left(\frac{W}{S}\right)\right]$$

Endurance:

$$\frac{HP}{W} = \frac{4}{550\eta_p} C_{D_O}^{1/4}\left(\frac{K}{3}\right)^{3/4}\left(\frac{2}{\rho}\frac{W}{S}\right)^{1/2}$$

Cruise:

$$\frac{HP}{W} = \frac{2}{550\eta_p} C_{D_O}^{1/4} K^{3/4}\left(\frac{2}{\rho}\frac{W}{S}\right)^{1/2}$$

Takeoff Distance:

$$\frac{HP}{W} = \frac{2.44}{550\eta_p}\frac{1}{g d_{to}}\left(\frac{1}{\rho_{SL} C_{L_{max}}}\frac{W}{S}\right)^{3/2}$$

Stall Condition

$$\frac{W}{S} = \frac{\rho}{2} C_{Lmax} V_{SO}^2$$

- Constraint equations governing feasibility & performance
- Matlab simulation mapping design choice consequences
- Narrowing design space given research goals

by Jessica Glass, undergraduate

NSF