Towards Proving Runtime Properties of Data-Driven Systems Using Safety Envelopes

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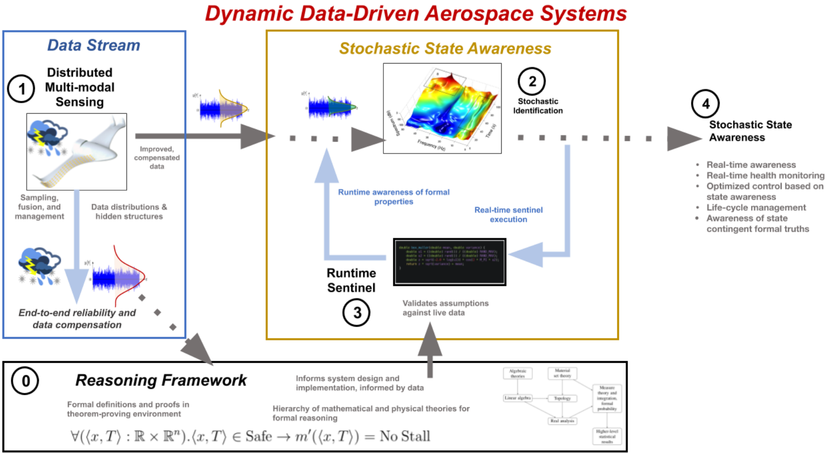
Dynamic Data Driven Aerospace Systems



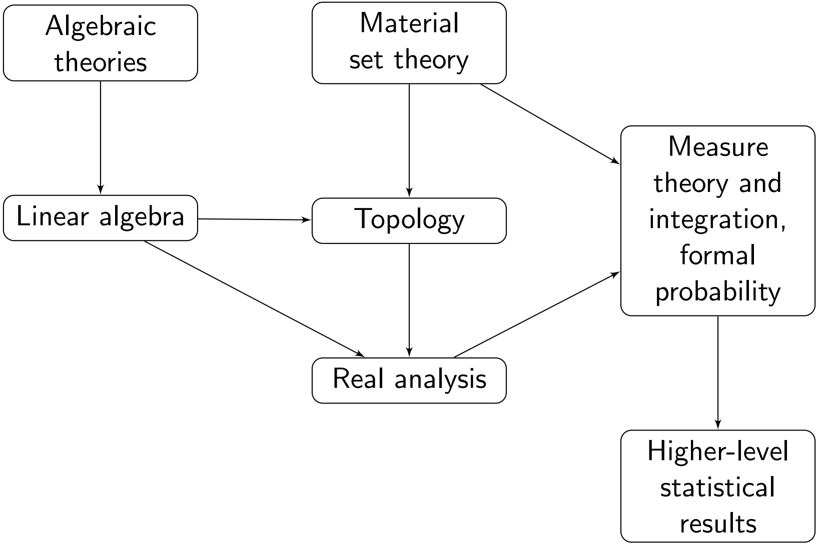
Overview

- Dynamic data-driven systems introduce complexity
- Often used in safety-critical domains (*e.g.* aerospace)
- Formal methods can yield stronger safety guarantees than testing

Formal Methods

- Computer-checked logical reasoning about a system
- Both automated and interactive approaches
- Requires a high level of rigor and detail, leading to high development costs
  - Magnified in systems involving stochastic elements
- Novel methods and techniques can help offset these costs

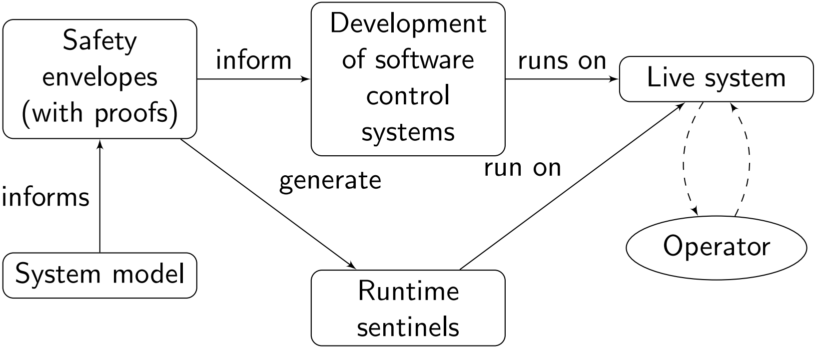
Hierarchy of Theories



Approach: Safety Envelopes

- Analogous to a flight safety envelope in an aircraft
- Describes a *safe subset* of system states
- Associates that safe subset with some correctness guarantee
- Provable formally in the proof assistant
- Checkable in live system through *runtime sentinel*

Workflow



Safety envelopes (with proofs)
inform
Development of software control systems
runs on
Live system
informs
generate
run on
System model
Runtime sentinels
Operator

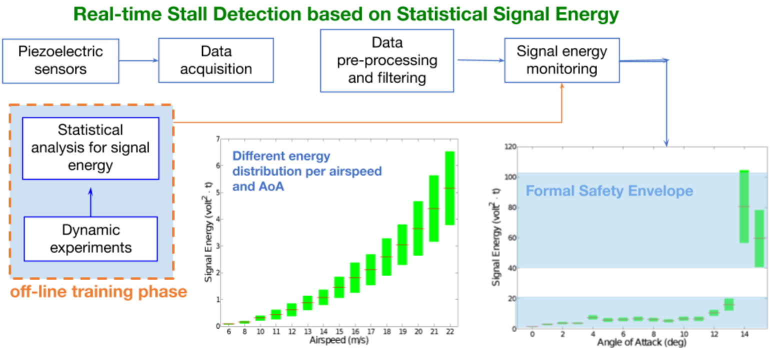
Runtime Sentinels

- Represent safe subsets as terms in some embedded domain-specific language
- Support evaluation to term in proof assistant
- Support generation of a program accessible from the runtime system
- Bring awareness of state-dependent formal properties to the system as it runs

Example: Introduction

- We study a model from Kopsaftopoulos associating a sensor reading from a wing with the likelihood that an aircraft is in a stall state
- Model is trained on experimental data from a wind tunnel - data driven
- We treat pairs of training data and runtime signal as system states
- Safe subset: intervals on runtime signal, (approximate) normality in training data

Example



Real-time Stall Detection based on Statistical Signal Energy
Piezoelectric sensors
Data acquisition
Data pre-processing and filtering
Signal energy monitoring
Statistical analysis for signal energy
Dynamic experiments
off-line training phase
Different energy distribution per airspeed and AoA
Signal Energy (volt² · t)
Airspeed (m/s)
Formal Safety Envelope
Angle of Attack (deg)

Example: Correctness

- Given definition of the model, we know that some intervals of runtime signal lead to "stall" classification
- Other intervals lead to "no stall" classification
- With appropriate definition of model, we can make this connection formal:

$$\forall(\langle x, T\rangle : \mathbb{R} \times \mathbb{R}^n).\langle x, T\rangle \in \mathrm{Safe} \rightarrow m'(\langle x, T\rangle) = \mathrm{No\ Stall}$$

Example: Sentinel

- C program testing membership in safe subset
- Using standard statistical tests for normality on training data
- Floating-point arithmetic for safe intervals of runtime signal
- Neither of these are "exact": disconnect between formal assumption and validation process
- Important area for future development