A modular framework for modeling hardware elements in distributed engine control systems

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Outline

1. Introduction
2. Modeling Framework
   - Baseline controller model
   - Distributed controller model
   - Summary of this modeling approach
3. Demonstrating the framework through simulation
4. Summary and Conclusion

Introduction

- Distributed control architecture has been slow to transition into aerospace applications because *challenges* perceived to **outweigh** *benefits*

Benefits

- Computational effort spread **across** the control system
- Engine control unit (ECU) not responsible for input/output conditioning
- **Digital** network replaces **analog** wiring, reducing complexity and weight of connections
- **Modularity** allows for easy replacement, upgrading, or maintenance of parts

Challenges

- Electronics needed to withstand **harsh engine environment**
- Specification and testing of **reliable controller network** must be done
- Collaboration to advance technology must **protect intellectual properties** of participants
- Testing of new hardware, control architectures is **limited** within present design process

Introduction

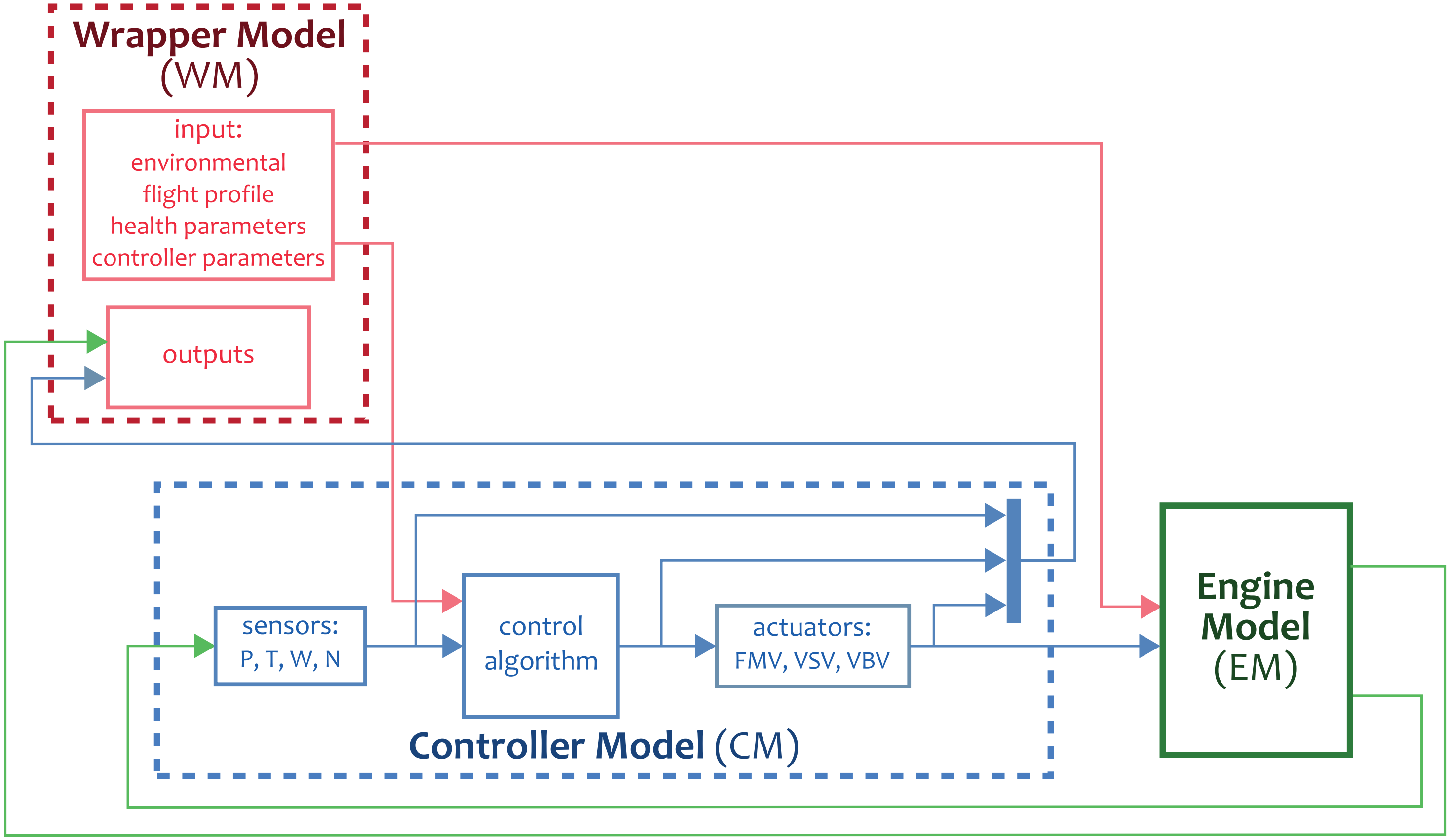
- A **h**ardware-**i**n-the-**l**oop (HIL) system is under development at NASA that will allow for testing hardware models and prototypes in various control configurations **without** the need for a physical engine
  - Control and engine design can proceed in **parallel**
  - Lowers the cost for hardware, controller testing
  - Simulation of conditions too extreme for test cells
  - Requires **high-fidelity** hardware and network models so simulations accurately represent tests on actual hardware
- **Interfaces** between elements of the control system, important in distributed architectures, can be leveraged to develop a modeling framework

Baseline controller model

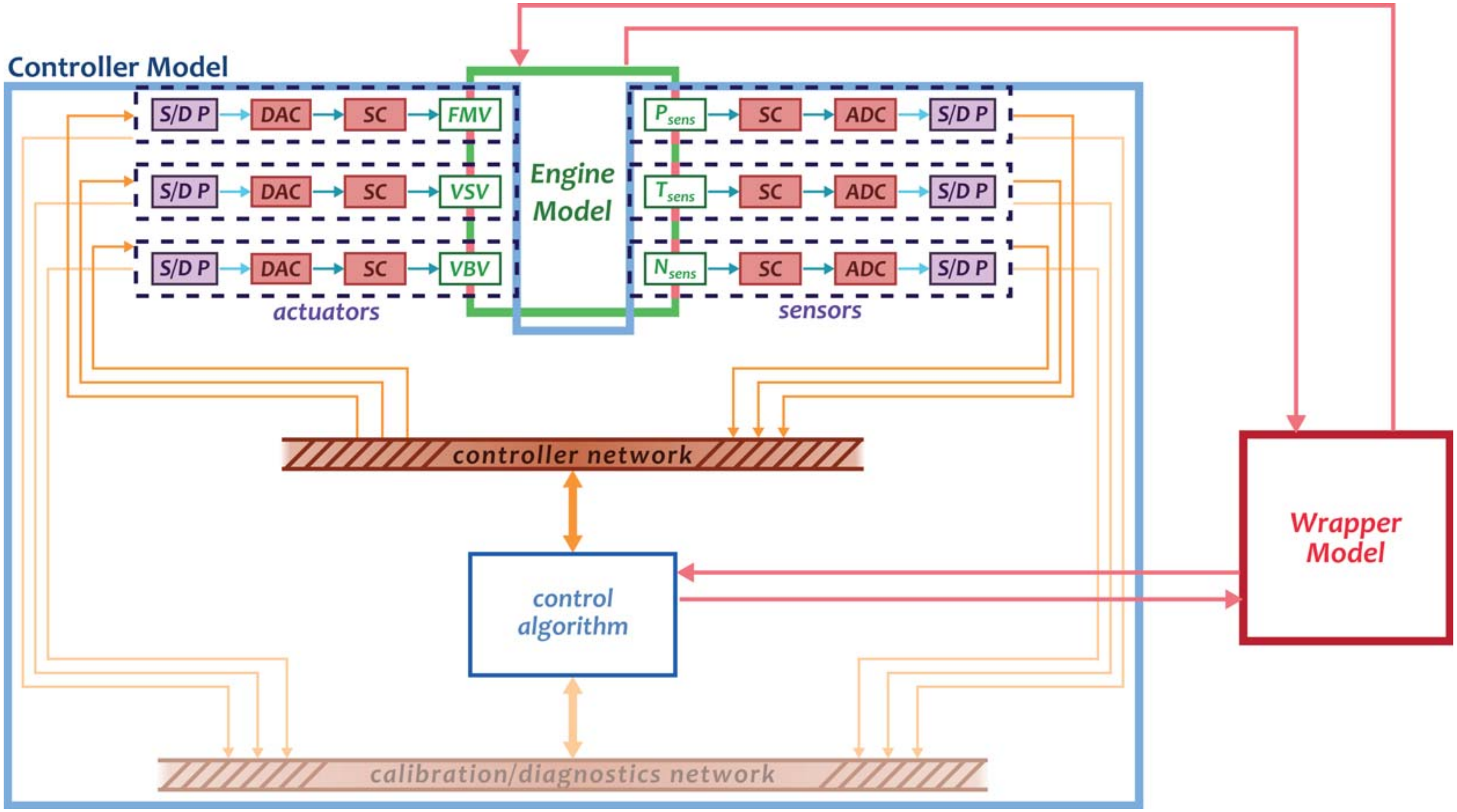
- Development of the system is around a baseline model: C-MAPSS40k (the ‘**unstructured**’ model)
  - **C**ommercial **M**odular **A**ero-**P**ropulsion **S**ystem **S**imulation, $40,000$ lb$_f$-thrust
  - Zero-dimensional simulation of a twin-spool turbofan engine
  - Controller contains **simple** sensor and actuator models along with setpoint controller and limiters
- **Structure introduced**, defining clear separation between engine and controller models

Baseline controller model

- **Two** sets of interfaces exist in this baseline system
  1. **Between** controller, engine and wrapper models
  2. **Within** controller model
  - May define a **third interface**: Connections **between components** on individual sensors, actuators



Distributed controller model



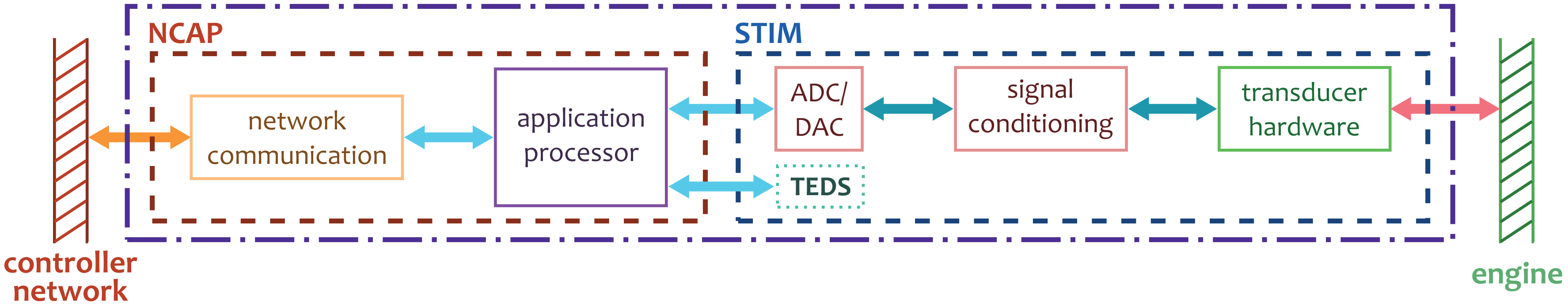
- Distributed controller model includes **data conditioning, conversion, and processing** on the sensors and actuators, and a **controller network**
- Higher fidelity computational models expected to **more closely match** results from tests with *real* hardware communicating over a **real** network

Distributed controller model

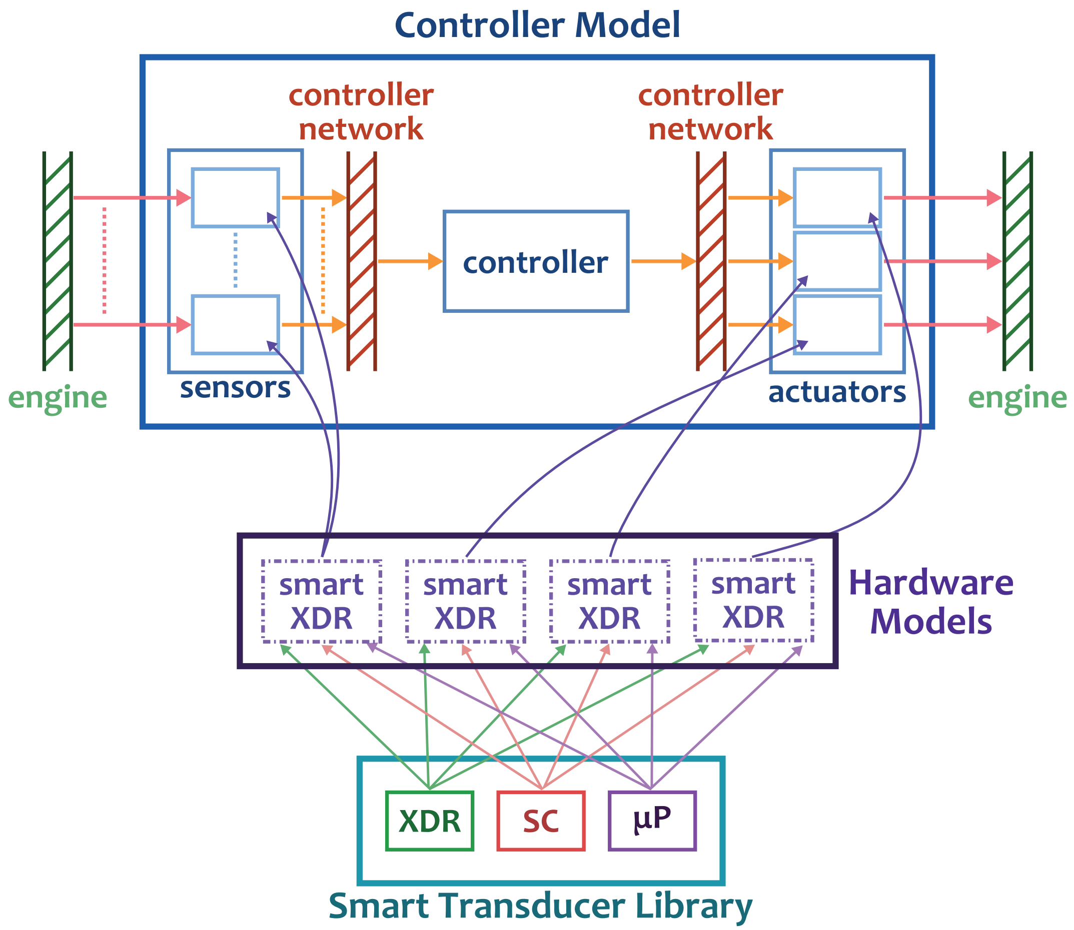
- Network represents **physical decoupling** of sensors, actuators, and the controller in an engine controller system
  - **Data transfer effects** need to be modeled to understand how these affect reliability and performance of closed-loop system
  - Presently modeled as a **delay** and **packet loss** (stochastically)
  - If higher fidelity is required, packet-level models may be constructed

Distributed controller model

- **Smart transducers** contain sensor or actuator hardware with local data conditioning and processing functionality
  - Simulink® library under development containing building blocks for modularly creating models of smart transducers
  - Library follows the **IEEE 1451 standard** for smart transducers
    - **S**mart **T**ransducer **I**nterface **M**odule (STIM) contains transducer, signal conditioning and conversion hardware (analog signals)
    - **N**etwork **C**apable **A**pplication **P**rocessor (NCAP) contains microprocessor and network adapter (digital signals)
    - **T**ransducer **E**lectronic **D**ata **S**heet (TEDS), stored on STIM, contains calibration and manufacturer information



Summary of this approach



- **Modularity** imposed at each level of the framework
  1. Between controller, engine, and wrapper models
  2. Between control hardware and control algorithm
  3. Within each smart transducer

Imposing this framework on C-MAPSS40k

- To demonstrate how framework affects simulation results, the C-MAPSS40k controller model was modified to follow it
  - **Replace sensor models** with smart sensor models (sensor, signal conditioning filter, analog-to-digital conversion and averaging blocks from Smart Sensor Library)
  - **Replace actuator models** with smart actuator models (extrapolation, digital-to-analog conversion, signal conditioning filter, and actuator library blocks)
  - **Add feedback sensors** for local loop closure on two actuators
  - Place **network block** on output of each sensor, input of each actuator
- **Three models** considered for comparison
  1. **Unstructured** model (baseline C-MAPSS40k controller)
  2. **Distributed** model (smart transducer models, no network)
  3. **Networked** model (smart transducer and network models)

Imposing this framework on C-MAPSS40k

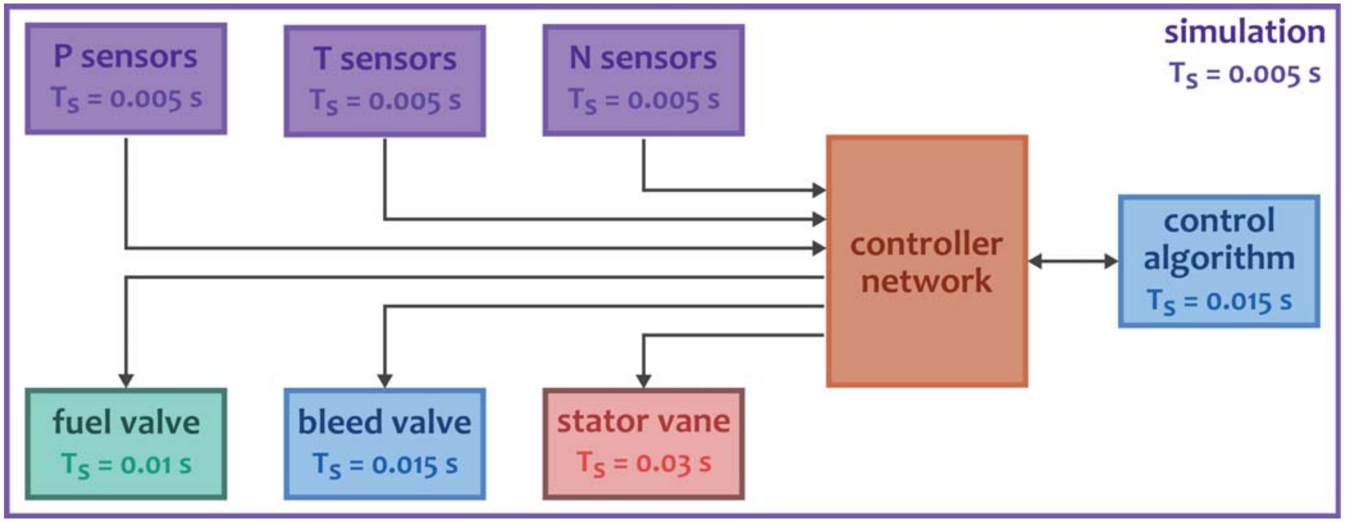
- Sensors and actuator configured using information from C-MAPSS40k for bandwidths, ranges; generic data sheets for conditioning, processing components
- Network model configured to **exaggerate** time delay, packet loss probability to better demonstrate effects of element

Sensor model configuration	
Sensor input range (psi)	0 to 30
Sensor output range (V)	0 to 0.07
Sensor rise time (s)	0.0879
ADC range (V)	-5 to 5
ADC resolution (bits)	8
Averaging window (sample)	3

Network cable model configuration	
Average delay (s)	0.001
Delay standard deviation (s)	0.003
Packet-drop probability (%)	15

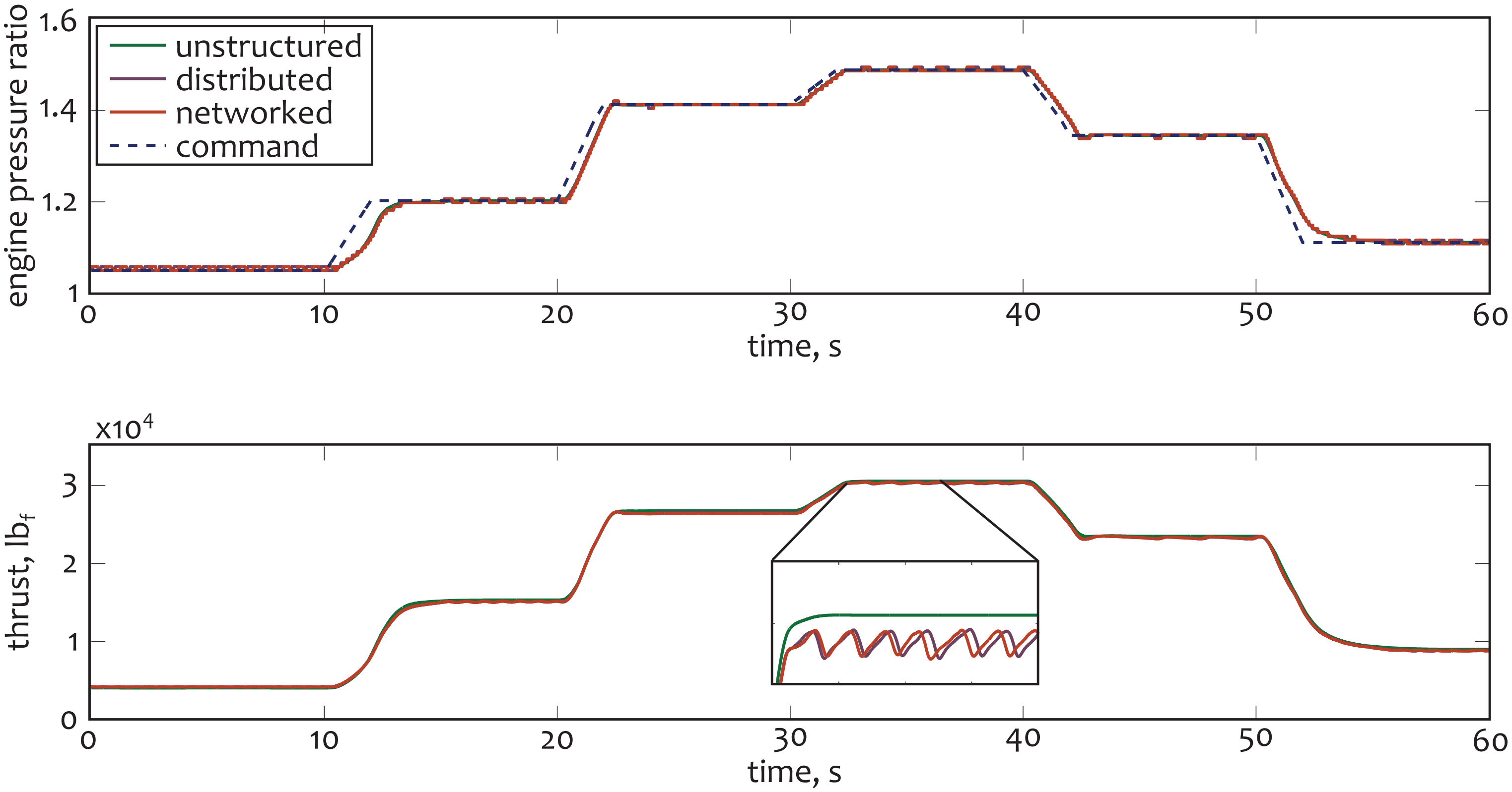
Imposing this framework on C-MAPSS40k

- Controller model further modified to allow for **multiple update rates** within simulation
    - **Baseline** model updates at a **fixed time-step** equal to the controller update rate
    - In **physical system**, each element operates **asynchronously** at its **own rate**
    - **Different (fixed) update rates** assigned to sensors, actuators, control law to improve realism of model
- Model can be viewed as collection of functions **accessing network at different rates**

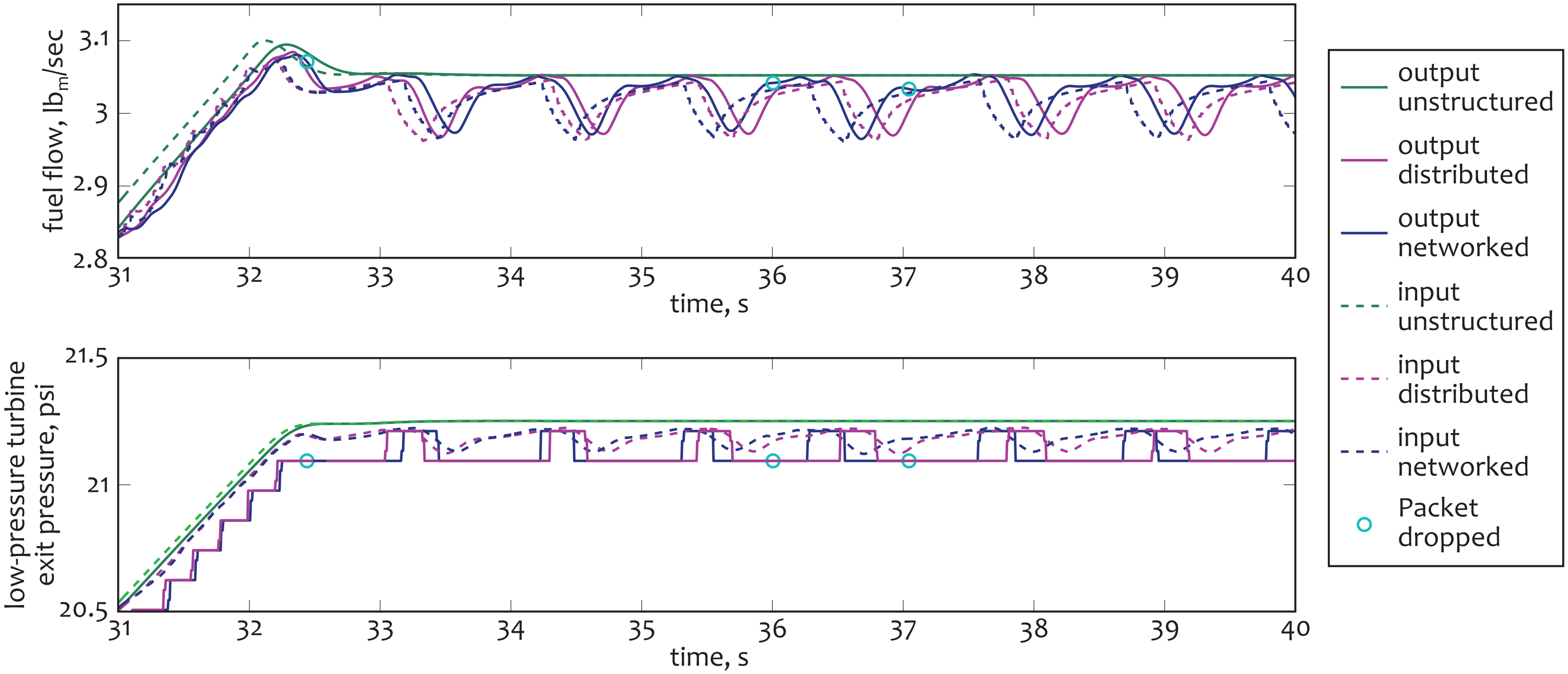


Comparing simulation results

- Provided a **60-second multi-step throttle command**
- Tracking and thrust responses **not significantly different**, despite more-detailed hardware models, presence of a network model

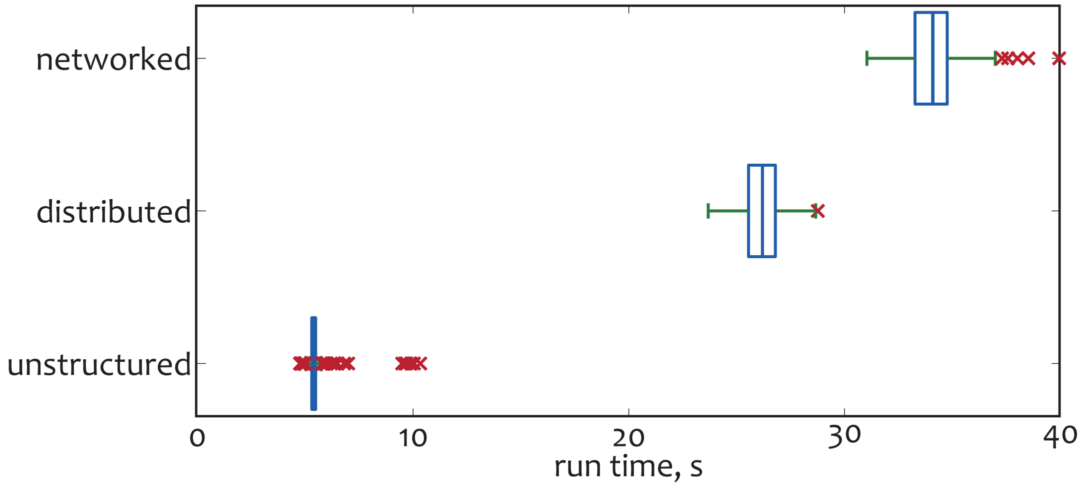


Comparing simulation results



- Biggest difference between simulation results seen by comparing outputs of actuators and sensors (here, fuel flow actuator and P_{50} sensor)
- Exaggerated network model **does not have much effect** on results

Comparing simulation results



- In addition to comparing simulation results, it is also important to verify that **real-time simulation** is possible
- Each model simulated 200 times, recording total run time
  - Variations likely due to processor demands during simulation
  - **Increased average time** for distributed and networked models due to **added complexity**
  - On average, distributed $(3.06$ times) and networked $(2.35$ times) models run **faster than real-time**, suggesting model may be run with hardware in the loop

Summary and Conclusion

- Framework presented for **developing models for hardware-in-the-loop systems**, based on **interfaces** present in the system
  - Between engine, controller, and user input source
  - Between control hardware and control law (over a network)
  - Within each individual piece of hardware
- Approach introduces **modularity**, enabling **independent development** of control algorithm, sensor, actuator, and engine models compatible with framework
- Simulink library, based on the IEEE 1451 framework, simplifies creation of **smart transducer hardware models**

Summary and Conclusion

- **Trade-offs** of this design choice must be weighed

Benefits

- Decoupled systems enable **collaboration**, **independent development** of models
- Protection of intellectual property by using **compiled code** in place of Simulink library blocks
- Use of Simulink library allows similar models with **varying fidelity** to be developed, interchanged easily

Drawbacks

- **Limited flexibility** of independent development at higher levels
- Models may relay information unnecessary for control algorithm, but needed for analysis, **adding complexity**
- More accurate models **increase computational cost**, real-time operation no longer guaranteed
- At this time, hardware and network models **not yet validated**, so simulations only act as proof-of-concept

Summary and Conclusion

- Simulation of C-MAPSS40k using this framework shows **quantization effects** in tracking
  - Overall results otherwise **differ little from baseline**
  - Simulation (on average) runs **faster than real-time**
- Future investigation may involve:
  - Validation of network model against physical network
  - Testing of framework in simulation with hardware in loop to verify accuracy of models in predicting actual system behavior

Thanks.

Questions?

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