

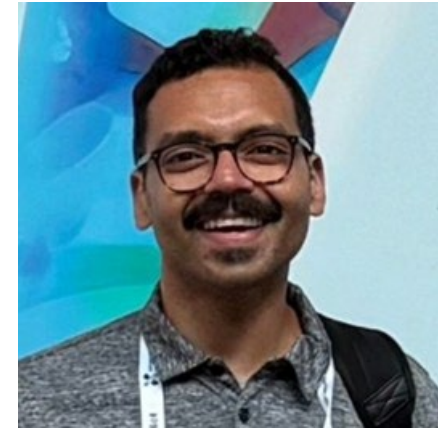
Sim-to-Flight: Why Starting With Simulation Is the Fastest Path To Successful Flight Testing



Dr. Anthony Comer
Assistant Professor
Oklahoma State University



Eric Hillsberg
Product Marketing Manager
MathWorks



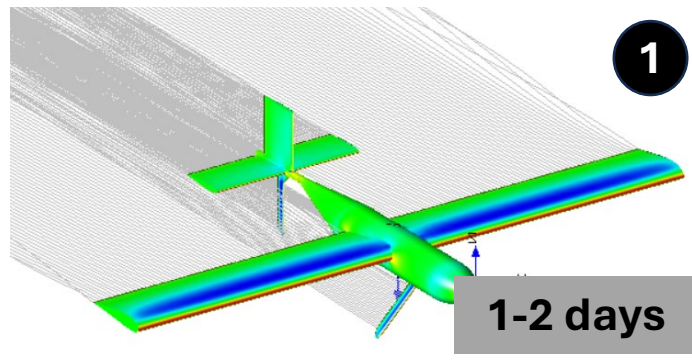
Ronal George
Senior Application Engineer
MathWorks



SCHOOL OF
**MECHANICAL AND
AEROSPACE ENGINEERING**
College of Engineering, Architecture and Technology



Simulation-to-Flight (S2F) Workflow



1

1-2 days

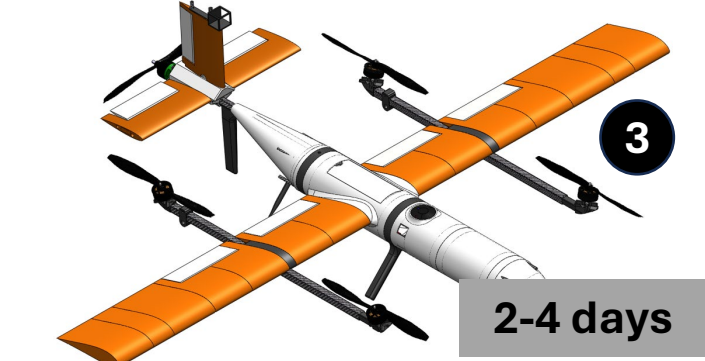
Vehicle geometry creation;
aero-propulsive modeling



2

2-3 days

Simulation model development;
flight control system design



3

2-4 days

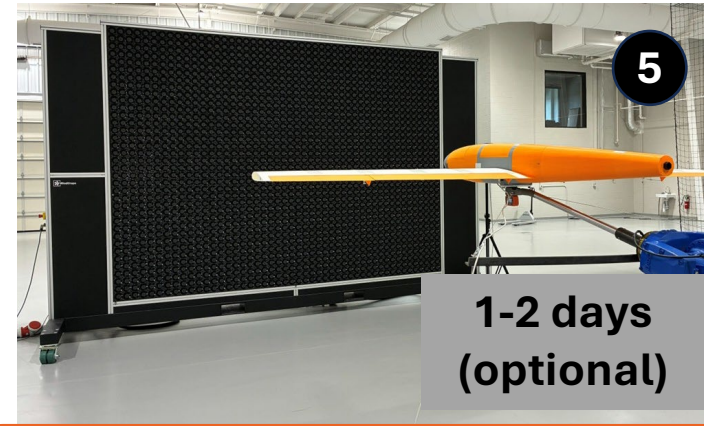
3D-printing parts; fabrication;
as-built characterization



4

1 day

Hardware and firmware
integration; HITL testing



5

1-2 days
(optional)

WindShaper tests; SYS ID; aero-
propulsive model validation



6

1-2 days

Flight tests; control law
validation; real-world checks

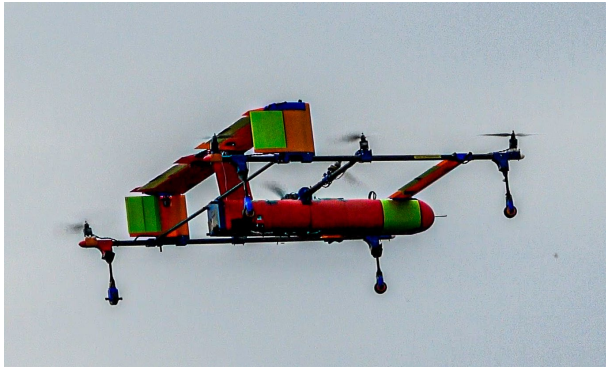
Flight Test Experience + Research Vehicles



Multi-Copter + Fixed-Wing



Lift + Cruise



Vectored-Thrust



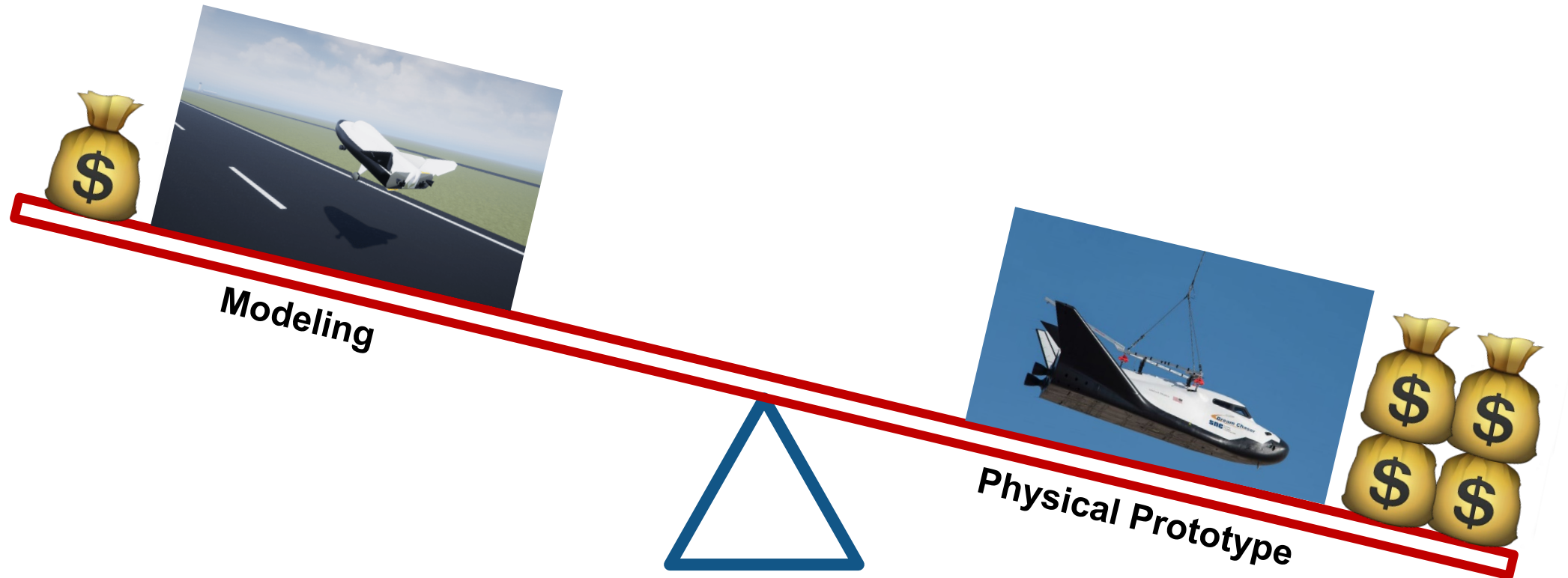
Tiltwing



Subscale Flight Testing for Flight Control Research



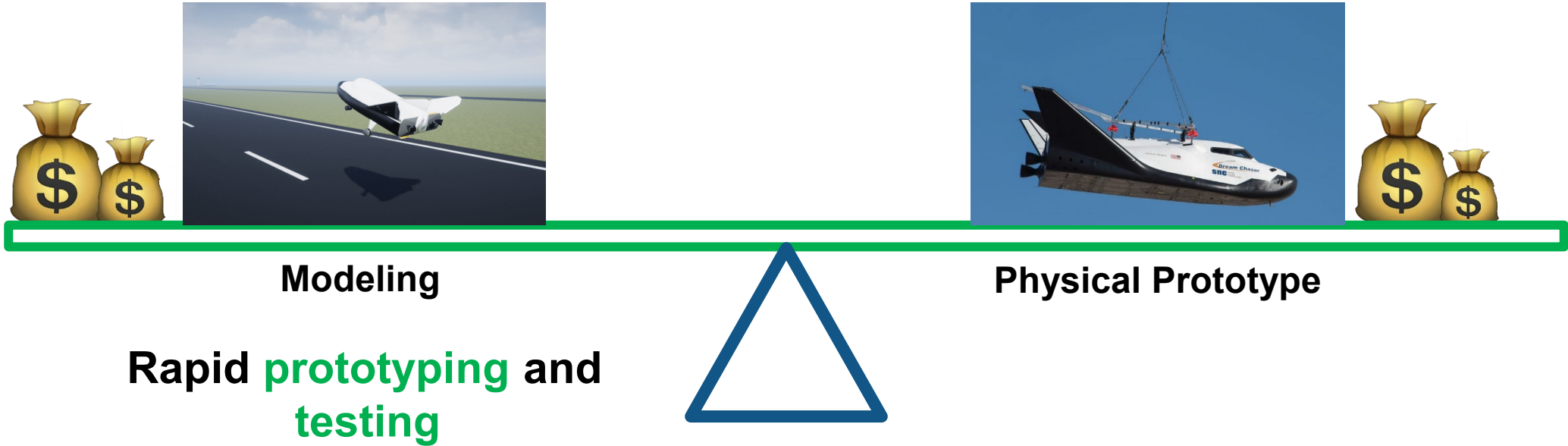
Physical prototypes are costly and iterate slowly



Design space **exploration**
Continuous design **improvement**

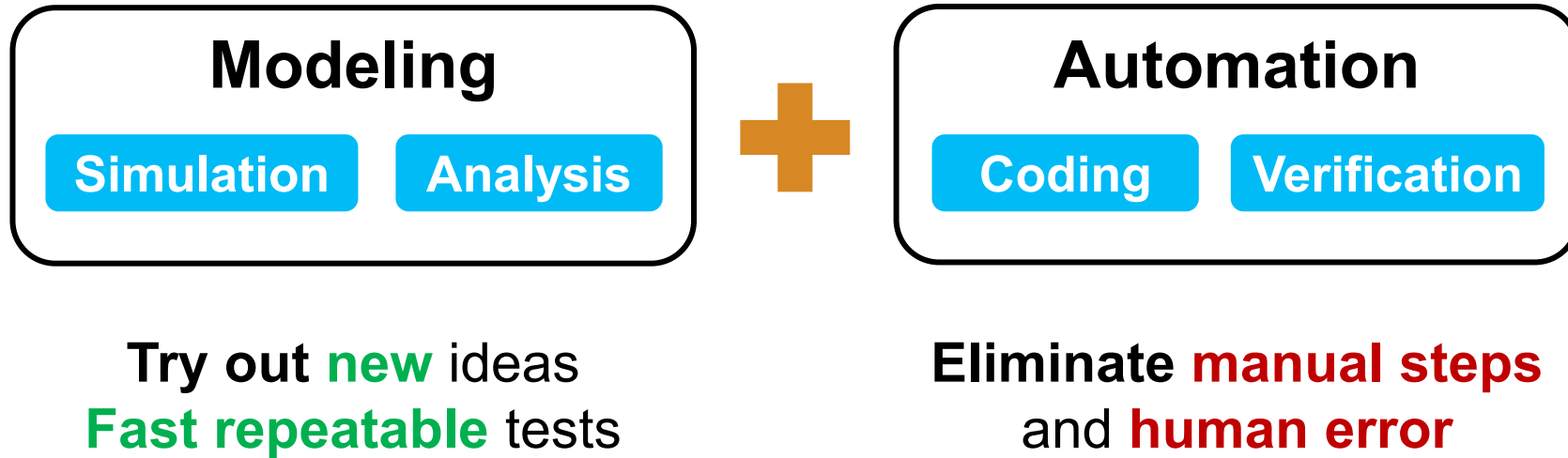
Costly and **time-consuming** to build
Hinders rapid iterations

Modeling and simulation help cut costs and speed up design iterations

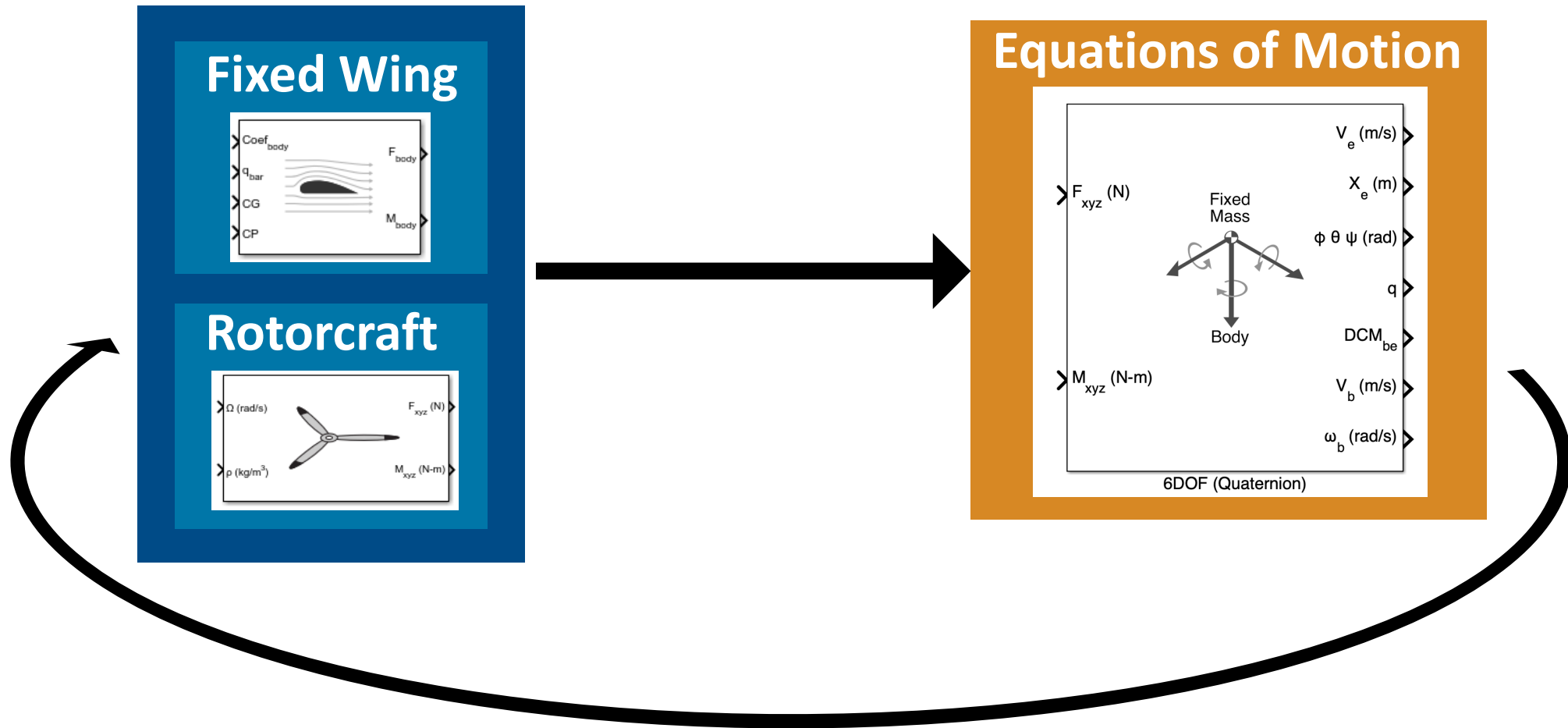


Model-Based Design

Systematic use of models throughout the development process

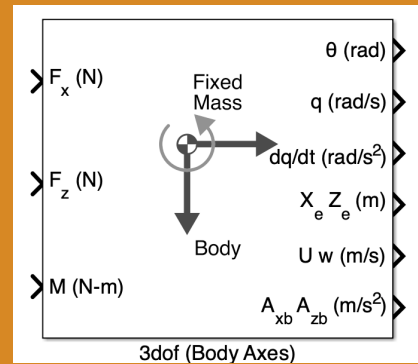
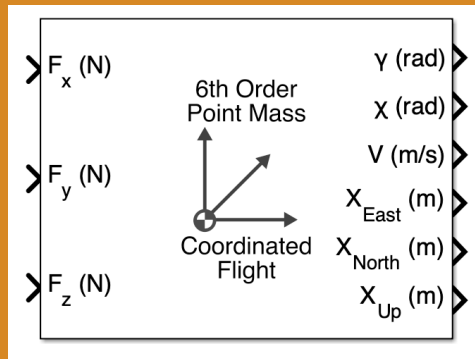
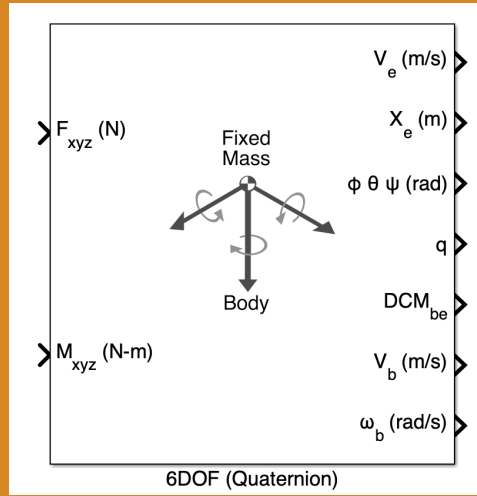


Aerospace Blockset enables modeling of Aircraft

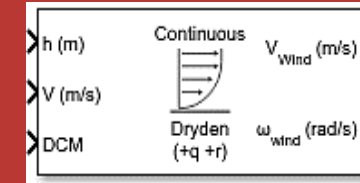
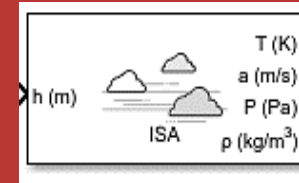


Dynamics modeled from first principles using Aerospace Blockset

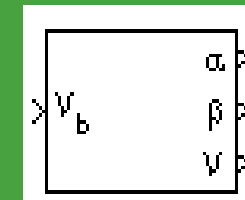
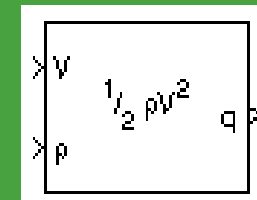
Equations of Motion:



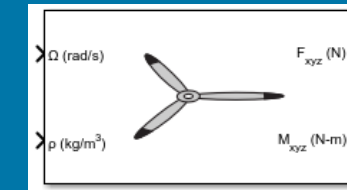
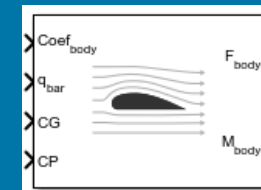
Environment:



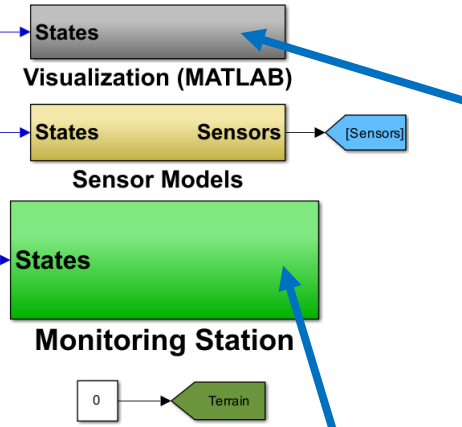
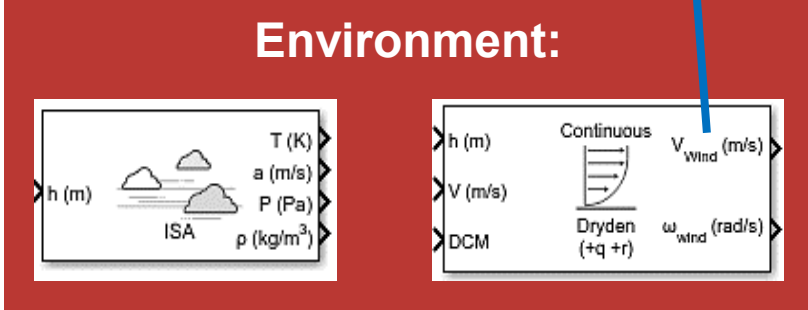
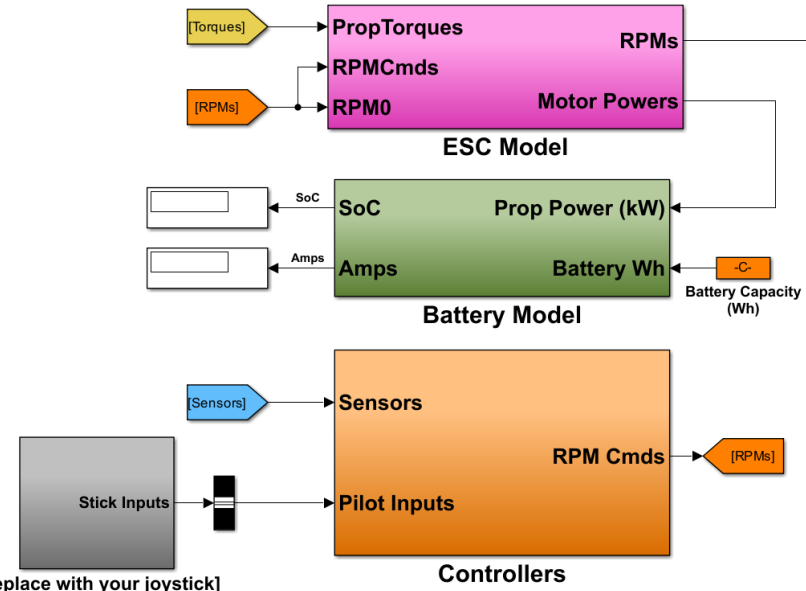
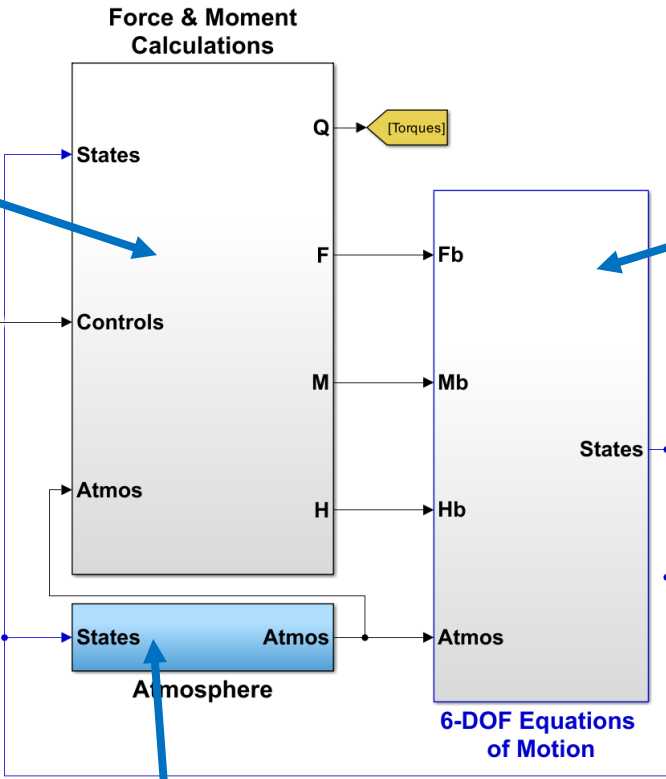
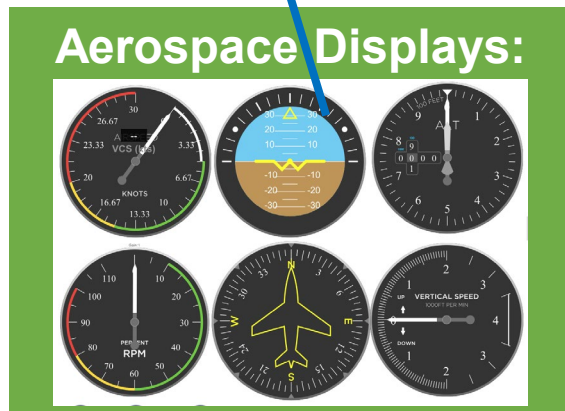
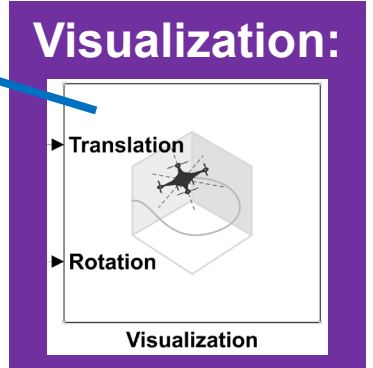
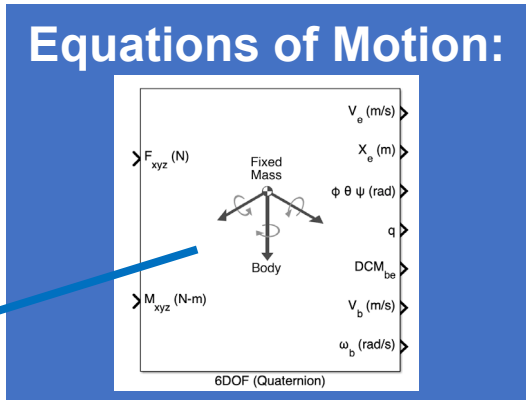
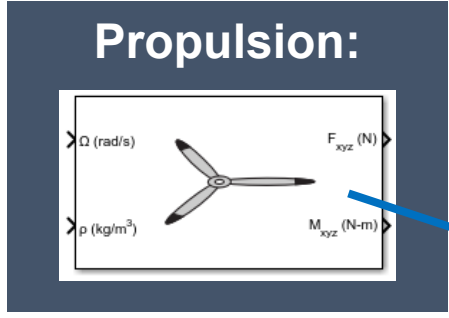
Utility Calculations:



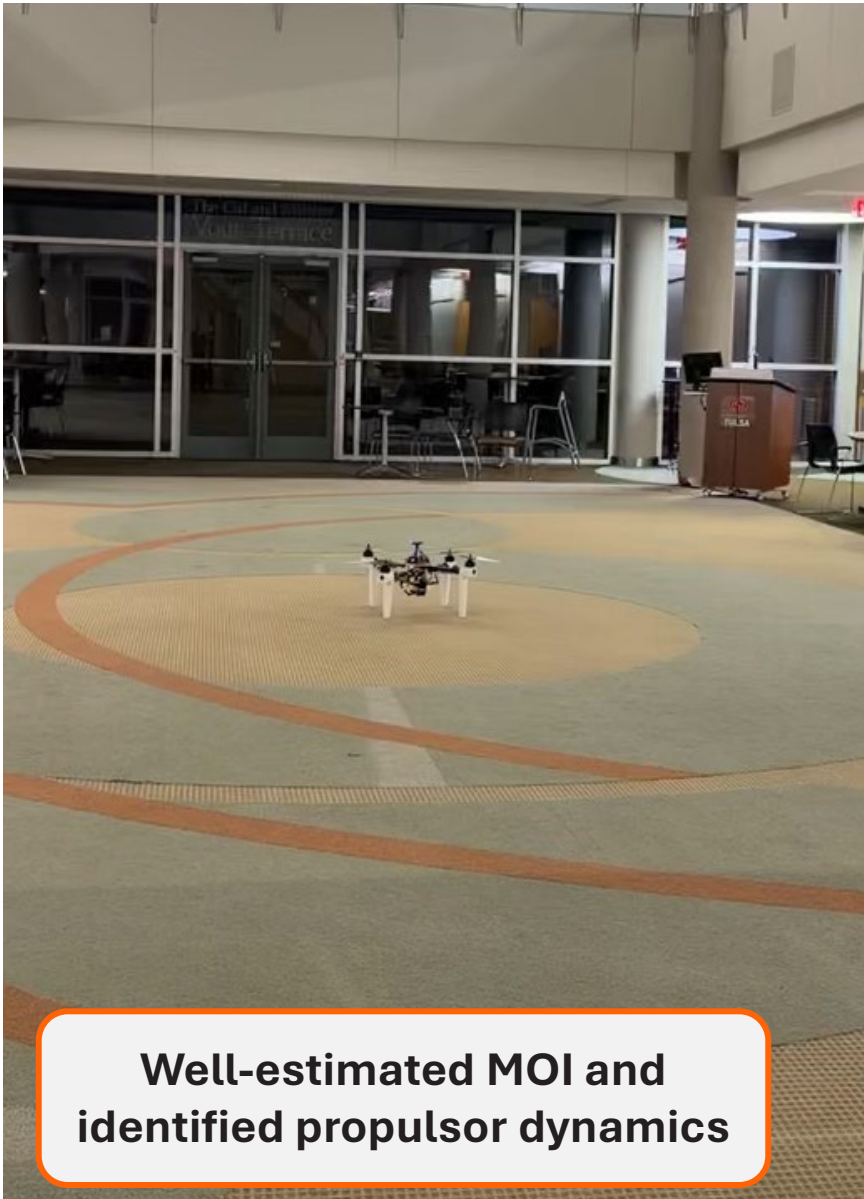
Aerodynamics and Propulsion:



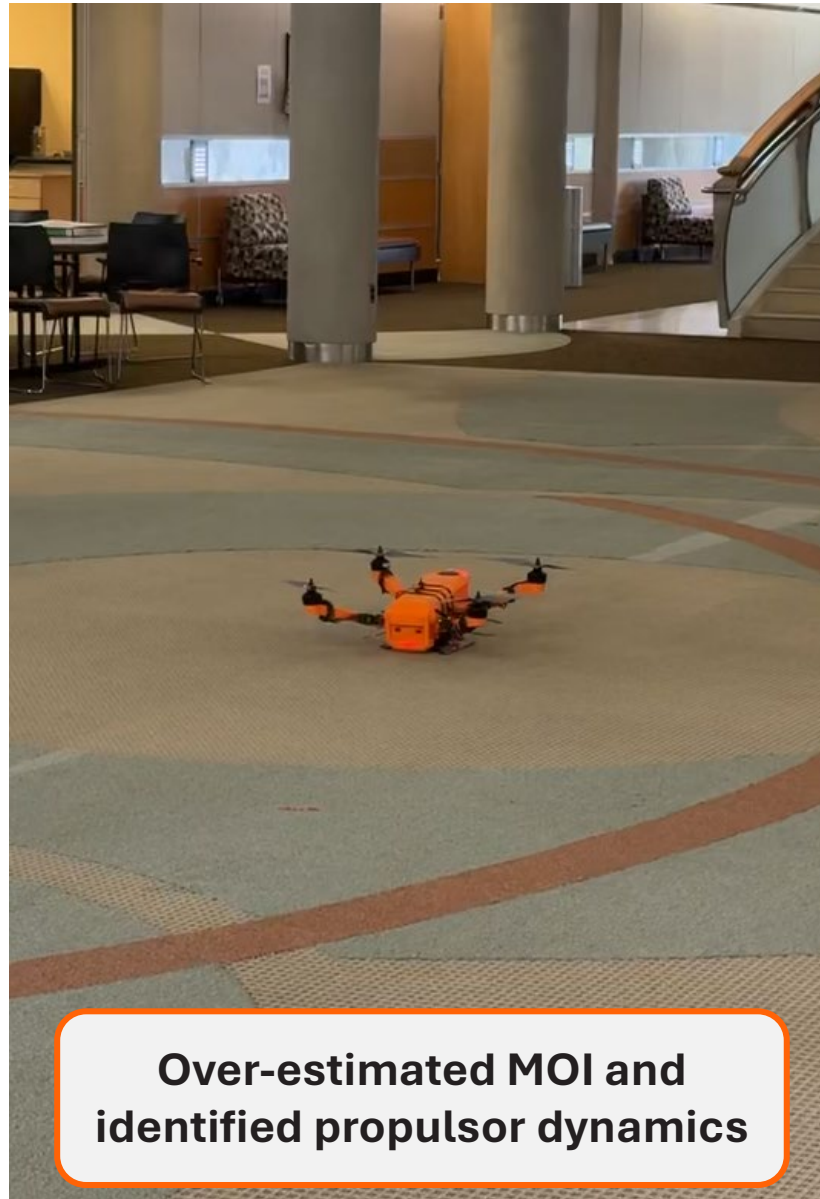
Simple Quad Model Using Aerospace Blockset



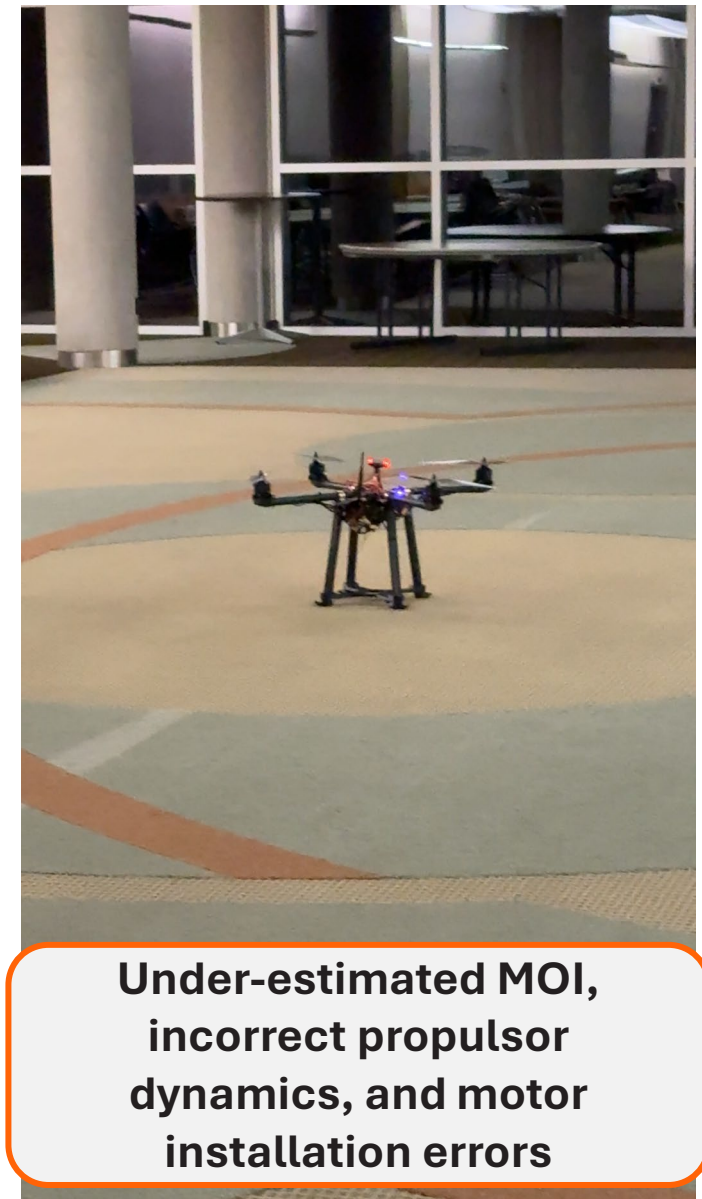
Quadcopter Flight Tests – Why Modeling Accuracy Matters



Well-estimated MOI and identified propulsor dynamics



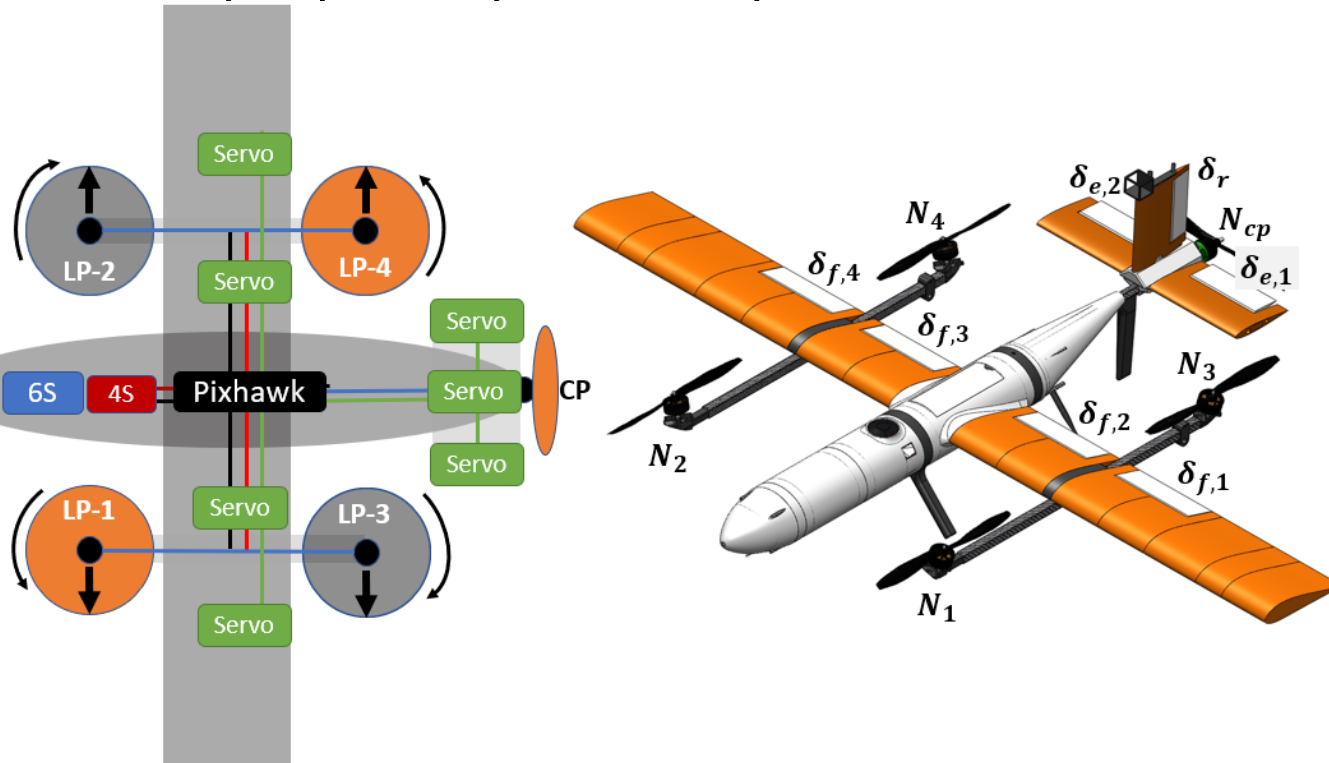
Over-estimated MOI and identified propulsor dynamics



Under-estimated MOI, incorrect propulsor dynamics, and motor installation errors

S2F-X200 Lift + Cruise Vehicle Overview

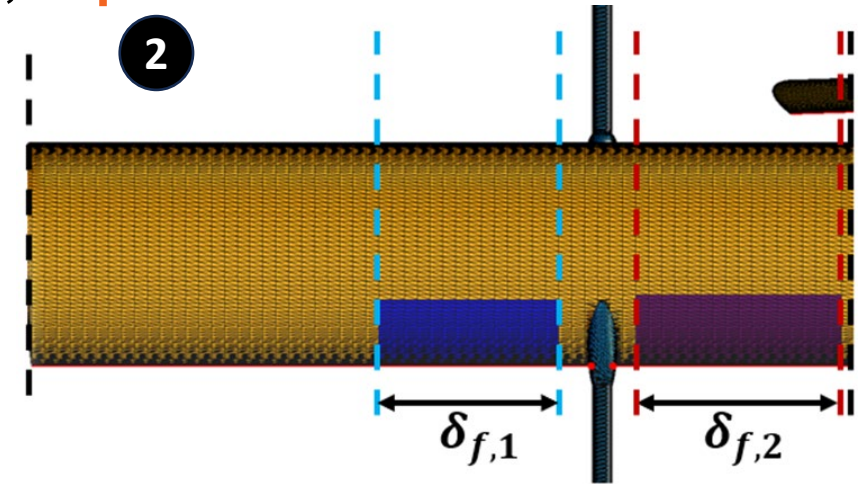
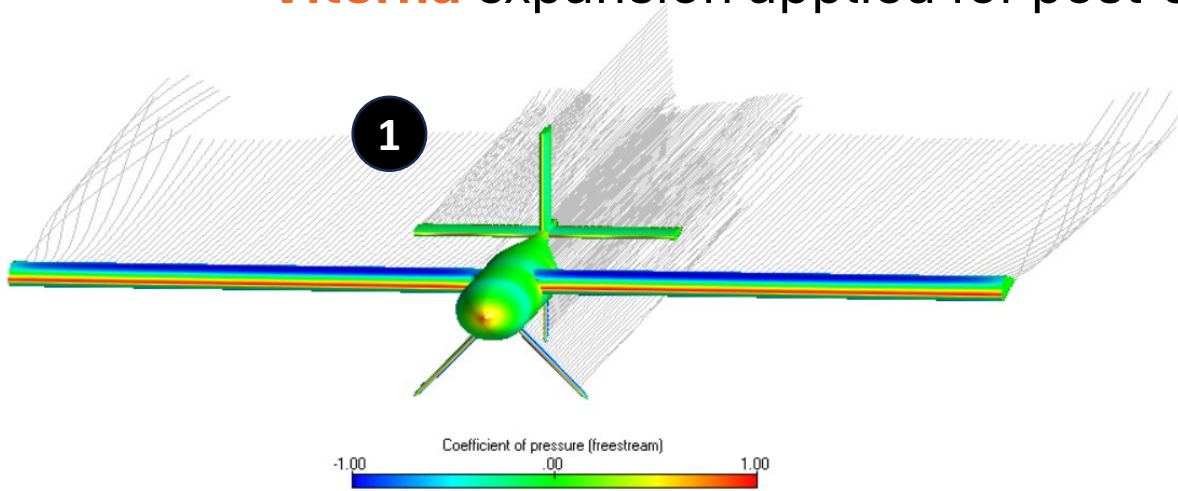
- **Group 2 lift + cruise eVTOL UAV (10.4 kg / 23 lbs)**
- **4** lifting props + **1** pusher-style cruise prop
- **2 m (6.56 ft)** wingspan – **6°** incidence
- Lift props are canted **outboard** by **15°**
- Ailerons, flaperons, elevators, and rudder



Parameter	Metric units	English units
Maximum takeoff mass (MTOM)	10.4 kg	23.0 lb
Empty takeoff mass (ETOM, w/o payload)	7.72 kg	17.0 lb
Battery mass	1.30 kg	2.86 lb
Payload mass	2.72 kg	6.00 lb
Moment of inertia, roll (I_{xx})	0.89 kg·m ²	21.1 lb·ft ²
Moment of inertia, pitch (I_{yy})	1.11 kg·m ²	26.3 lb·ft ²
Moment of inertia, yaw (I_{zz})	1.72 kg·m ²	40.8 lb·ft ²
Product of inertia (I_{xz})	0.07 kg·m ²	1.66 lb·ft ²
Wing area	0.50 m ²	5.42 ft ²
Wing span	2.00 m	6.97 ft
Horizontal tail span	0.58 m	1.92 ft
Vertical tail span	0.20 m	0.67 ft
Fuselage length	1.47 m	4.81 ft
Lift propeller diameter	0.39 m	15.5 in
Lift propeller cant angle	±15°	±15°
Lift motor rated power (each)	4 × 1375 W	4 × 1.84 hp
Cruise propeller diameter	0.38 m	16.0 in
Cruise motor rated power	1200 W	1.61 hp
Wing loading (ETOM)	15.4 kg/m ²	3.16 lb/ft ²
Disc loading (ETOM, hover)	15.9 kg/m ²	3.26 lb/ft ²

Aerodynamic Modeling - FlightStream

- Vehicle geometry definition begins in **OpenVSP**
- The geometry is then imported into **FlightStream**, a mid-fidelity surface-vorticity solver capable of performing aerodynamic sweeps in **minutes**
- Aerodynamic models are developed in one of the following **two** methods:
 1. Full-Model (coefficient look-up table)
 - Aerodynamic **coefficients** determined from sweeps and **queried** as $c_{(\cdot)} = f(\alpha, \beta, Re)$
 2. Strip-Theory (Reduced Order **downwash** Model (ROM) model)
 - Sectional **coefficients** are determined from XFOIL and **queried** as $c_{(\cdot)} = f(\alpha, \beta, Re)$
 - **Viterna** expansion applied for post-stall conditions [1]; **slipstream** effects are modeled



Propulsion Modeling – Data Fitting Approach

- Experimental or APC **Data Fitting** (polynomial fitting)
- Useful for very **high frequency** data requirements (150+ Hz)
- Propeller **characteristics** (thrust, torque, and power) are determined from existing data and **computed** as $[T, Q, P] = f(N, \theta_{AOI}, V, \rho)$

$$X = a_0 + a_1N + a_2V + a_3N^2 + a_4NV + a_5V^2 + a_6N^3 + a_7N^2V + a_8NV^2 + a_9V^3$$

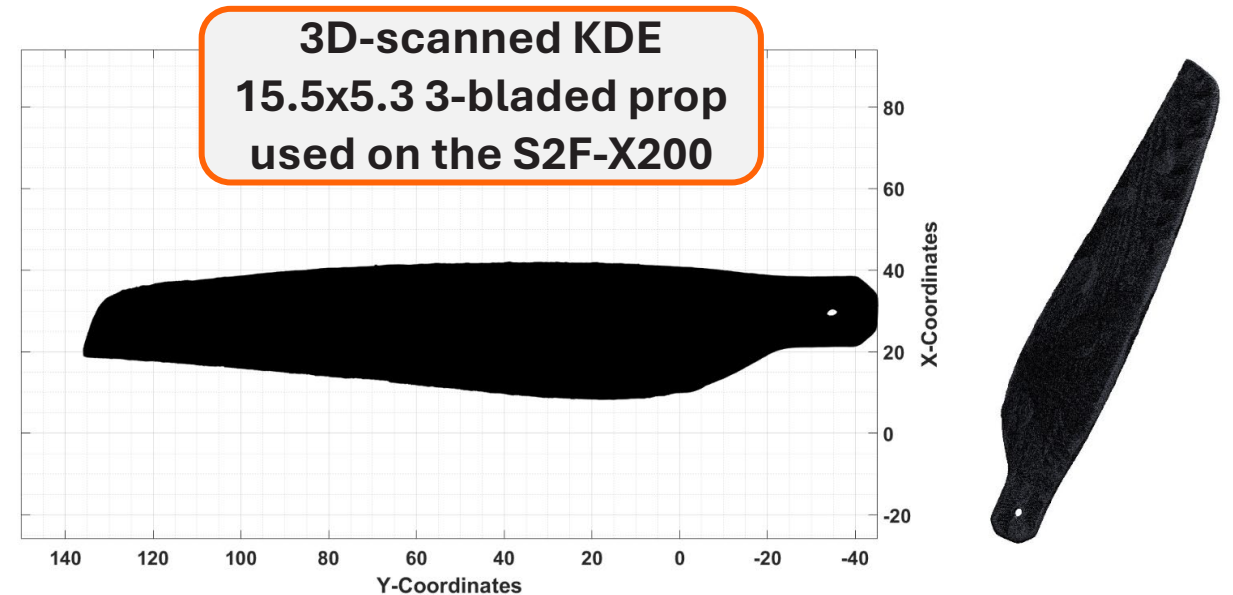
- Velocity can either be axial, freestream, or edgewise depending on the configuration and available data
 - **Local** velocity changes due to vehicle **motion** are also considered
- Non-axial flow propulsion data is collected using a **WindShaper** (*described later*)

**Fittings from APC
16x5.5 MRP (LP) and
APC 15x10E (CP)**

Propulsor	Coefficients									
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9
LP (T)	-0.20	2.06e-04	-0.03	≈ 0	-1.34e-04	-0.03	≈ 0	≈ 0	-2.54e-06	5.02e-04
LP (Q)	-0.01	1.21e-05	9.12e-05	≈ 0	5.75e-07	-9.76e-04	≈ 0	≈ 0	≈ 0	-8.38e-06
LP (P)	-9.12	8.55e-03	-1.36	≈ 0	4.61e-04	0.11	≈ 0	≈ 0	-1.08e-04	-6.29e-03
CP (T)	-0.29	2.64e-04	-0.02	≈ 0	-5.50e-05	-0.02	≈ 0	≈ 0	-2.45e-06	2.72e-04
CP (Q)	-0.01	1.80e-05	-6.70e-04	≈ 0	4.45e-06	-1.35e-03	≈ 0	≈ 0	7.54e-08	-1.34e-05
CP (P)	-20.54	0.02	-0.85	≈ 0	-1.22e-04	0.11	≈ 0	≈ 0	-9.91e-05	-0.01

Propulsion Modeling – BET + DIM

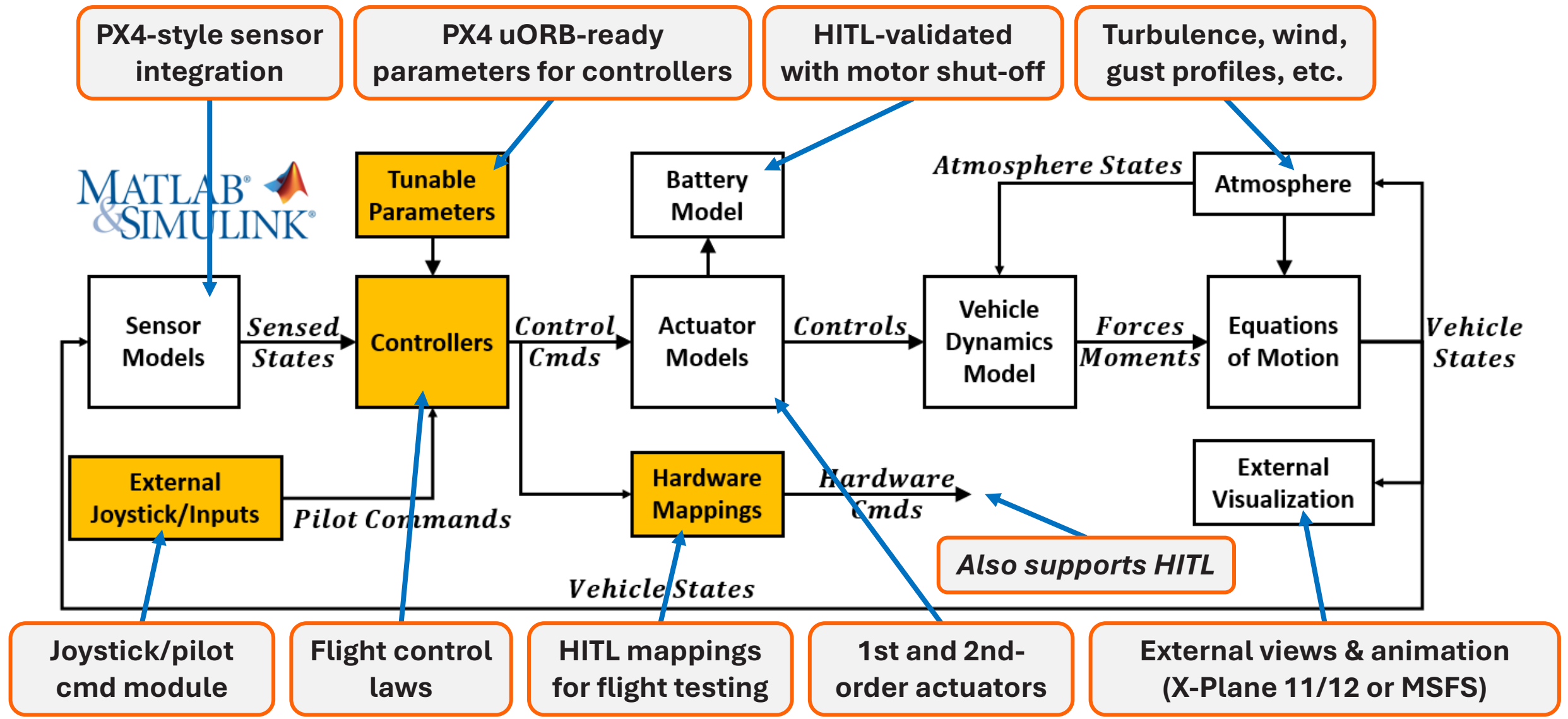
- Blade Element Theory (**BET**) + Dynamic Inflow Model (**DIM**)
 - **Inflow** is computed using a first-order Pitt-Peters and Zhao dynamic inflow model with wake **skew** and **curvature** effects [2]
- Propeller blades are **discretized** into geometric strips based on **geometric** data (if available); otherwise, blade geometry is developed using a **3D-scanner**
 - Airfoil data is determined from Palmo/FlightStream and **Reynolds number** changes are considered
 - For **multiple airfoils**, a **linear** taper is used between airfoil characteristics
- Flow **acceleration** is modeled for blown strips
- Slipstream is modeled as a **super-Gaussian** wake profile [3]
- The incorporation of **wake skew** effects on the strip-theory model are being tested



VISTA Simulation Model Overview

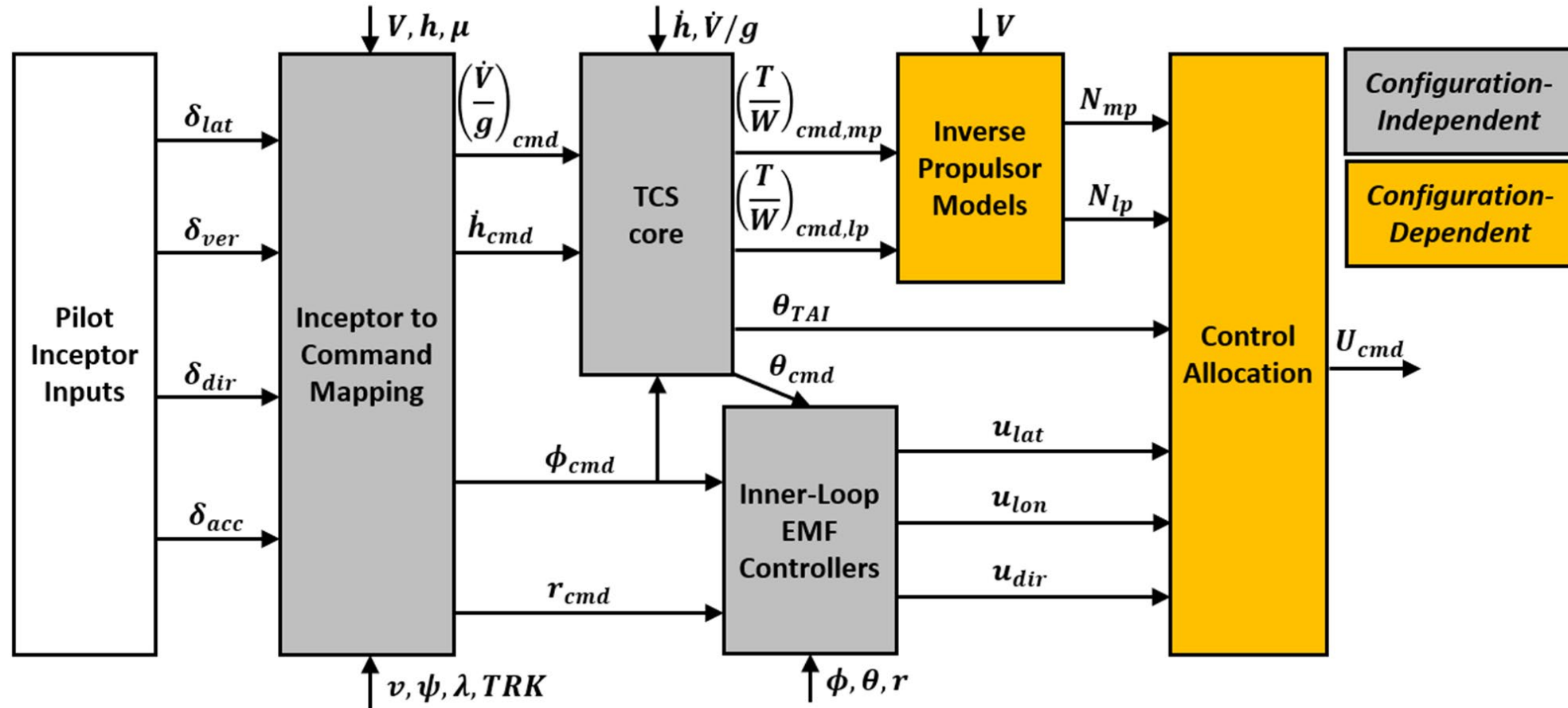
- **Versatile Integrated Simulation and Testing Architecture** (VISTA) is a **MATLAB/Simulink-based** simulation environment developed for **rapid** digital twinning and **hardware integration**
- Additional **tools** include:
 - **Trim Analysis** – trim algorithm developed around the **generality** of the Trajectory Control System [3], capable of trimming **over-actuated** vehicles
 - **Model Linearization** – numerical model **linearization** about specified trim conditions for use in control law design and optimization
 - **Flight Control Optimization** – the *Fast Algorithm for Control Optimization* (FALCO) tool, developed to support **user-defined optimization** of novel control systems
 - **Real-Time Simulation** – a Simulink model capable of running at **100+ Hz** on desktop computers for **real-time** simulation and **piloted studies**
 - **External Interfaces and Visualization** – ready to connect to common **peripherals** (e.g., joysticks, other computers {multiplayer}, motion platforms); **HITL-ready**; works with X-Plane 12 / MSFS for **external visualization**; a **full guide** for vehicle animation is provided in a recent NASA TM by Comer, Simmons, and Asper [4]

VISTA Simulink Model



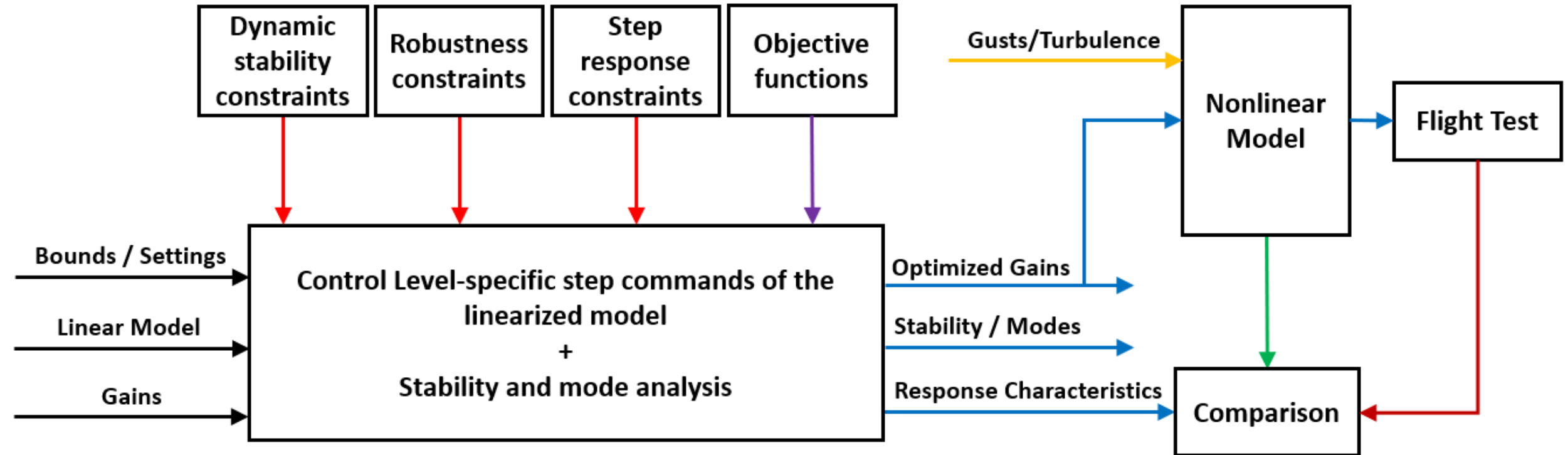
Flight Control System Architecture (Overview)

- **Simplified Vehicle Operations (SVO)** paradigm: making the vehicle **easy to fly**
- **Inceptor to Command Mapping (ICM)** for pilot-autonomy task-sharing
- **Trajectory Control System (TCS)** for **coordinated** vertical and horizontal trajectory control
- **Explicit Model Following (EMF)** inner-loop attitude controllers (RCAH & ACAH)

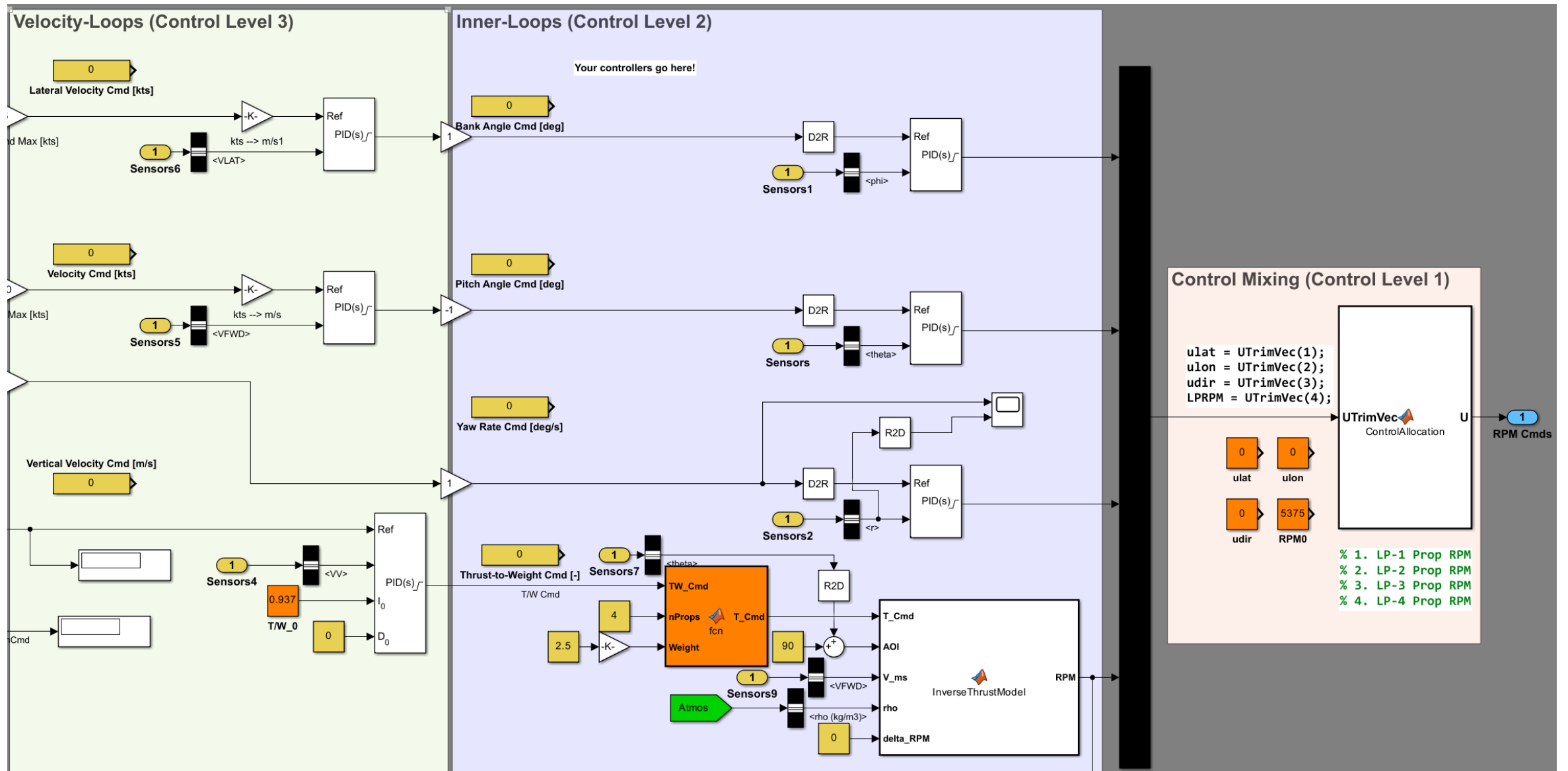


Fast ALgorithm for Controller Optimization (FALCO)

- The **linearized** models at each trim condition are subjected to the MATLAB **genetic algorithm** function *ga* with several nonlinear constraints
 - **Dynamic stability** constraints (e.g., damping ratio, damping)
 - **Robustness** constraints (e.g., gain and phase margin, crossover frequency, disturbance rejection)
 - **Step response** characteristics (e.g., rise time, settling time, overshoot)



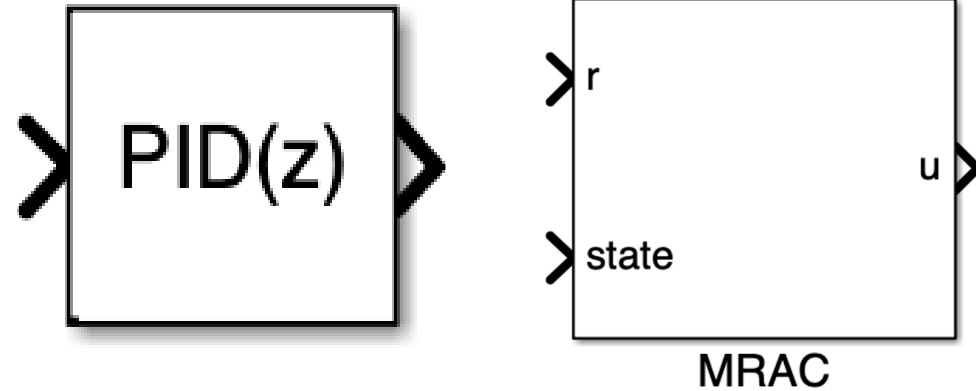
Cascaded PIDs in Simulink for Control Design



Why use Simulink for Controls?

- Pre-built Simulink blocks

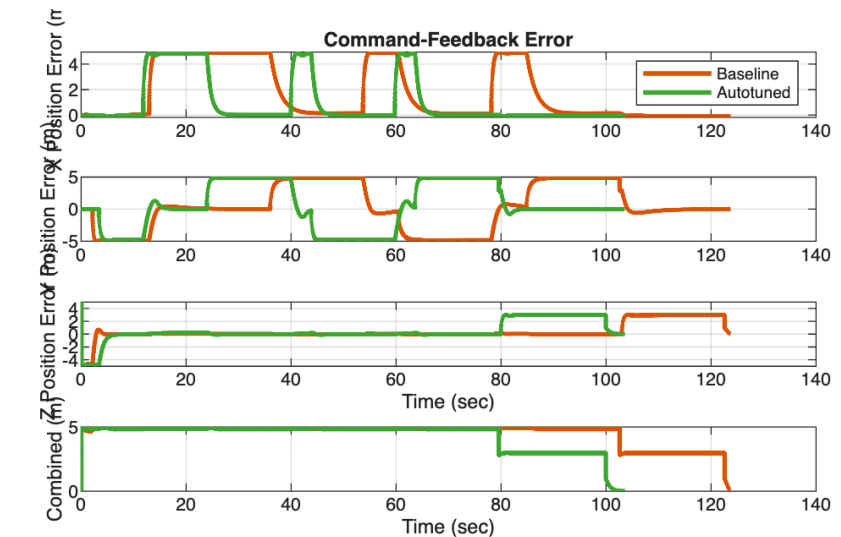
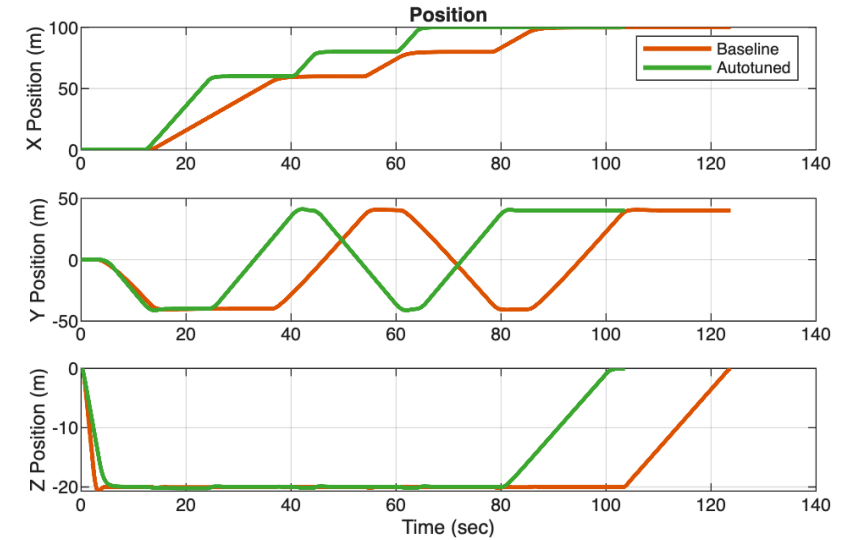
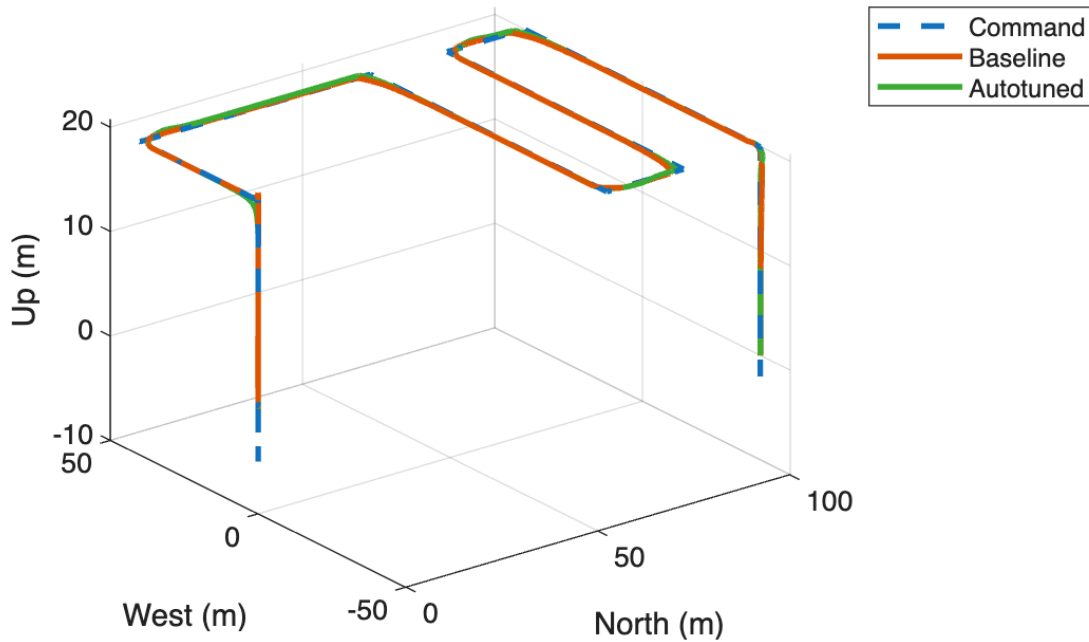
Required products:
Simulink Control Design



- Efficient code generation for resource-constrained hardware



You can improve performance with less effort through Autotuning

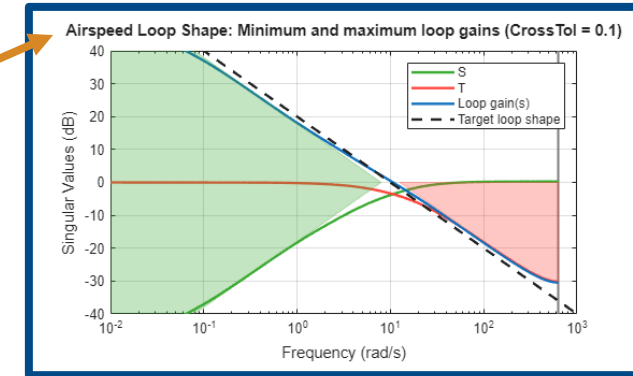
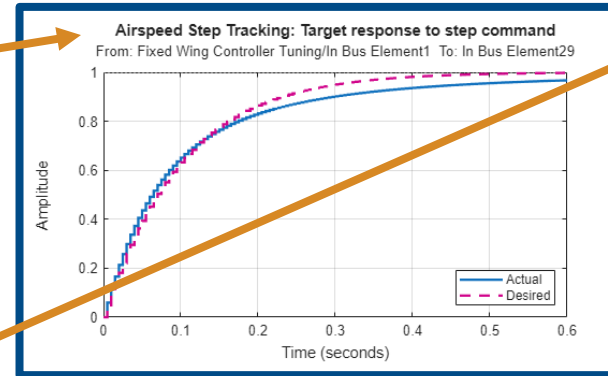


Autotuned Average Error: 4.3296 meters

Baseline Average Error: 4.5434 meters

If highly cross-coupled or want more control use systemtune

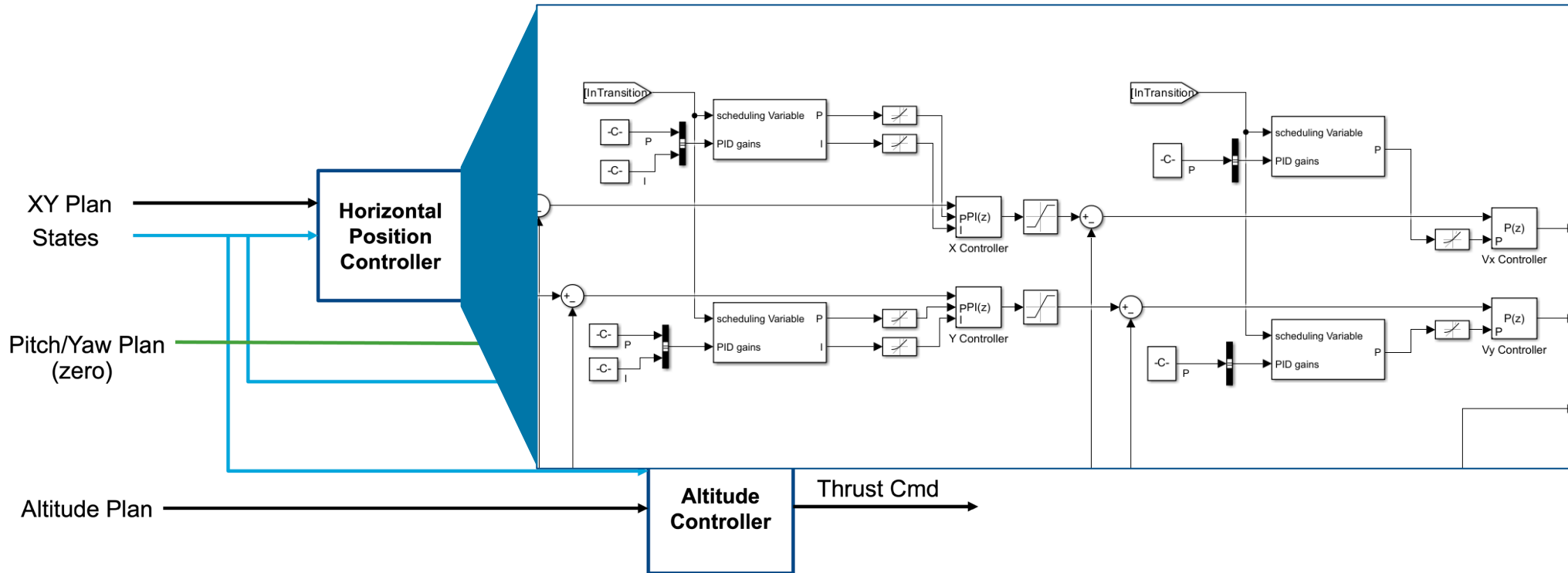
Time-Domain Requirements	
TuningGoal.LQG	Linear-Quadratic-Gaussian (LQG) goal for control system tuning
TuningGoal.StepRejection	Step disturbance rejection requirement for control system tuning
TuningGoal.StepTracking	Step response requirement for control system tuning
TuningGoal.Transient	Transient matching requirement for control system tuning
Frequency-Domain Requirements	
TuningGoal.Gain	Gain constraint for control system tuning
TuningGoal.Overshoot	Overshoot constraint for control system tuning
TuningGoal.Rejection	Disturbance rejection requirement for control system tuning
TuningGoal.Sensitivity	Sensitivity requirement for control system tuning
TuningGoal.Tracking	Tracking requirement for control system tuning
TuningGoal.Variance	Noise amplification constraint for control system tuning
TuningGoal.WeightedGain	Frequency-weighted gain constraint for control system tuning
TuningGoal.WeightedVariance	Frequency-weighted H_2 norm constraint for control system tuning
Loop Shapes and Stability Margins	
TuningGoal.LoopShape	Target loop shape for control system tuning
TuningGoal.Margins	Stability margin requirement for control system tuning
TuningGoal.MaxLoopGain	Maximum loop gain constraint for control system tuning
TuningGoal.MinLoopGain	Minimum loop gain constraint for control system tuning
Passivity and Sector Bounds	
TuningGoal.ConicSector	Sector bound for control system tuning
TuningGoal.Passivity	Passivity constraint for control system tuning
TuningGoal.WeightedPassivity	Frequency-weighted passivity constraint
System Dynamics	
TuningGoal.ControllerPoles	Constraint on controller dynamics for control system tuning
TuningGoal.Poles	Constraint on control system dynamics



This model has an [example](#) for the Fixed Wing configuration of the VTOL. You can set many tuning goals and visualize tuning results.

```
>>openExample('uav/TuneControlDesignForUAVInFixedWingFlightExample')
```

Autotuning can be leveraged to Gain Schedule

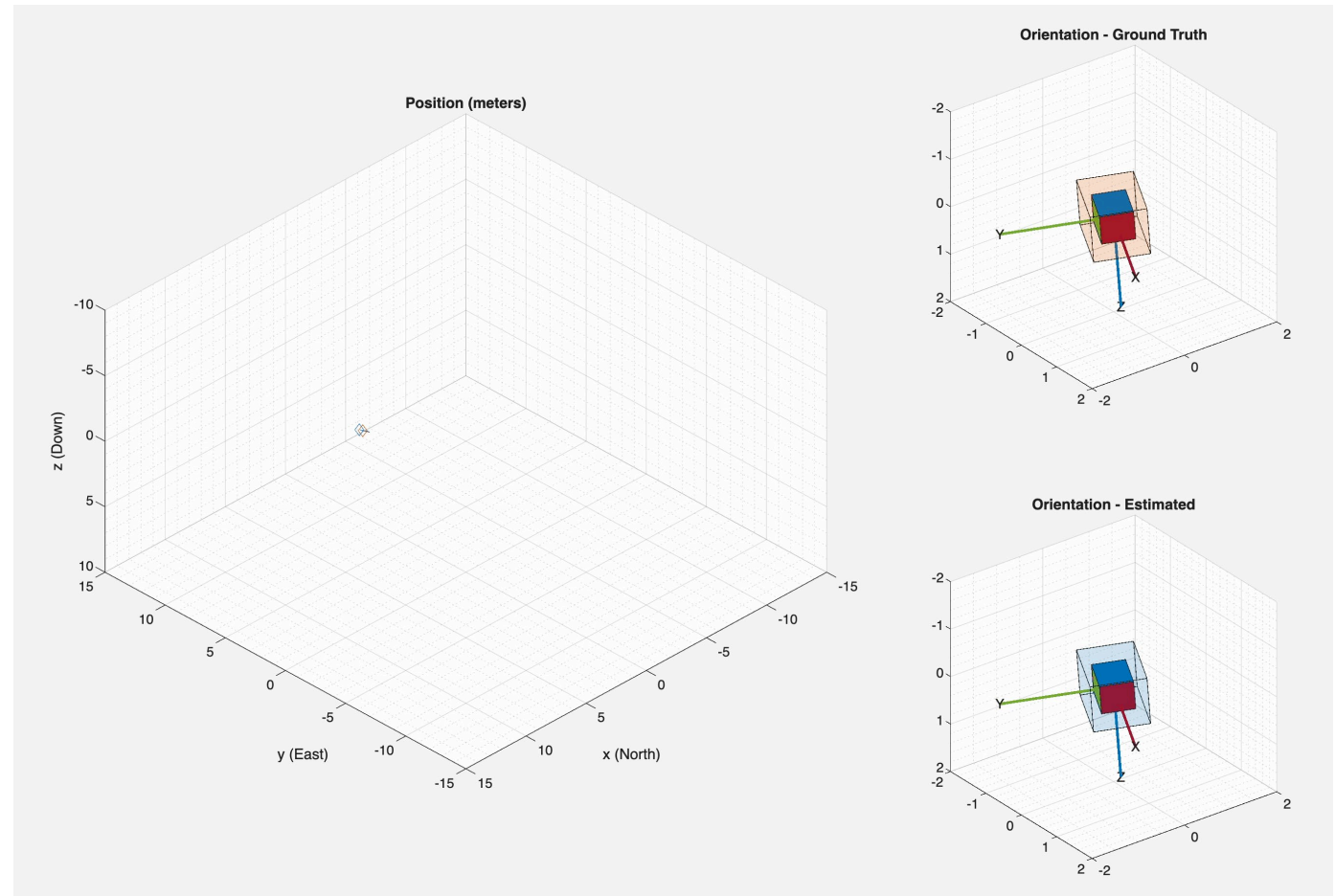
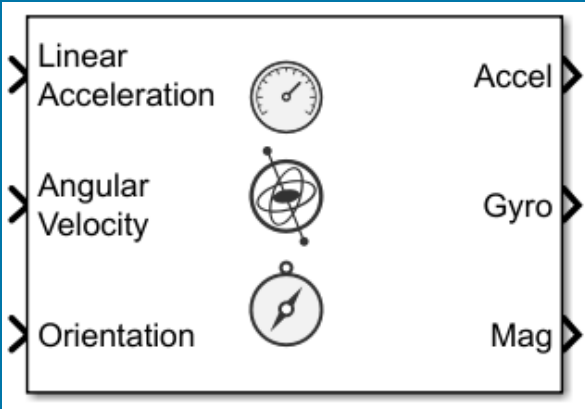
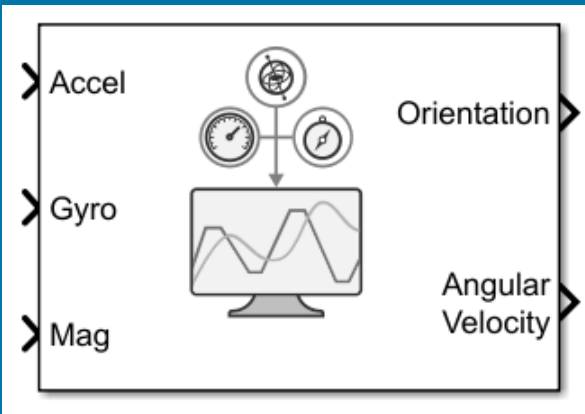


In fact, we have an [example](#) which shows how to do this for a VTOL transition.

```
>> openExample('slcontrol/GainScheduledPIDAutotuningVTOLDuringTransitionExample')
```

You can Test Your Perception and Navigation Systems With Navigation Toolbox

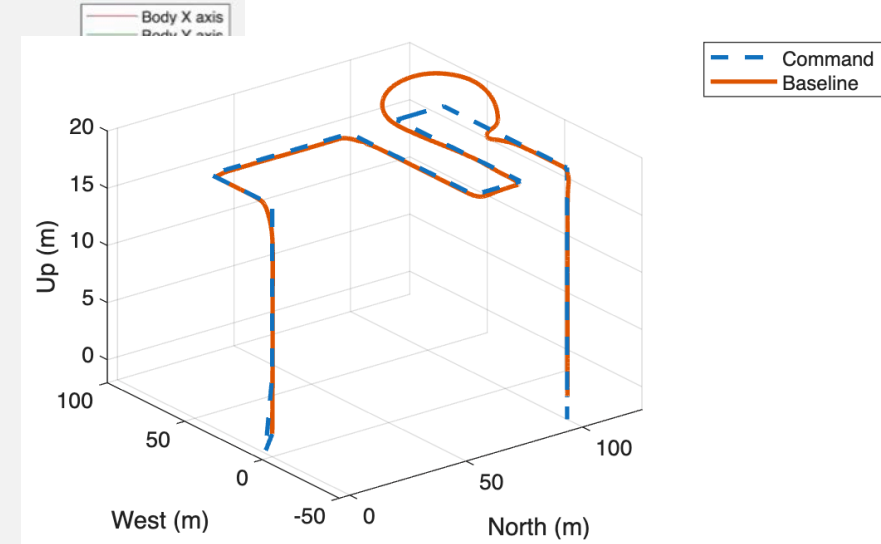
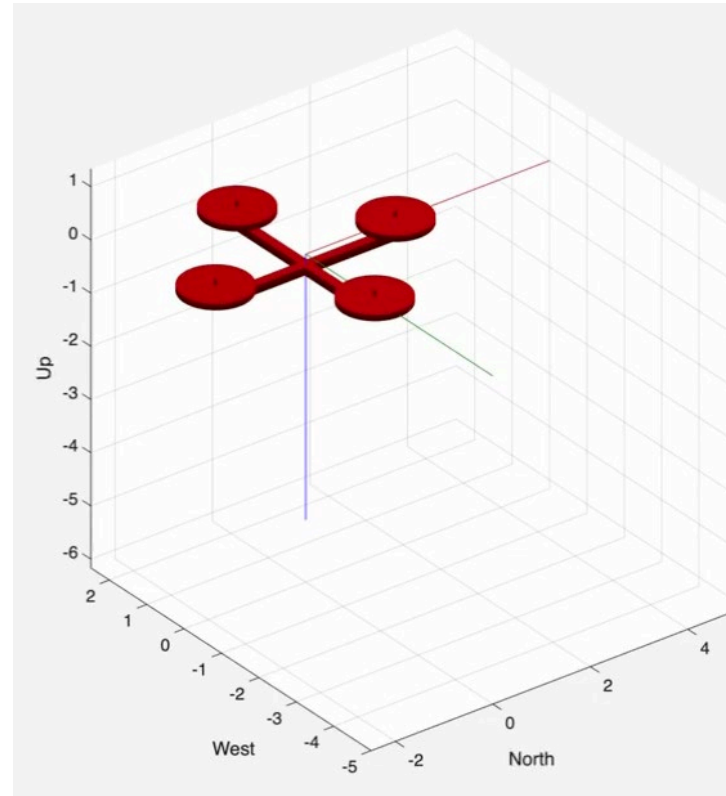
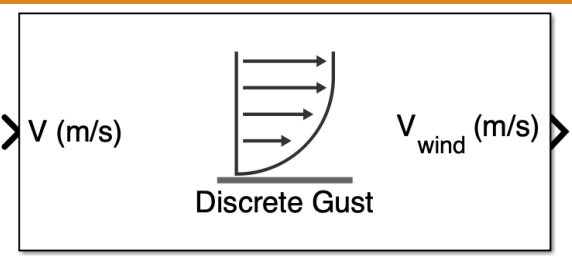
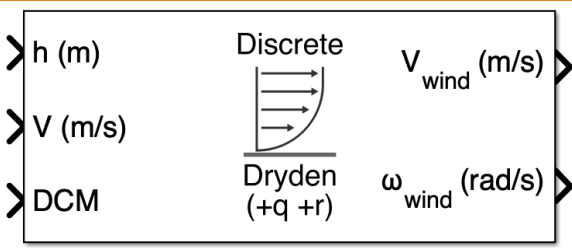
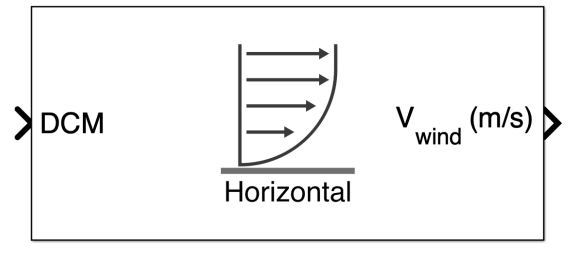
Sensors and Filters



You can capture environmental effects

With Aerospace Blockset

Wind and Turbulence



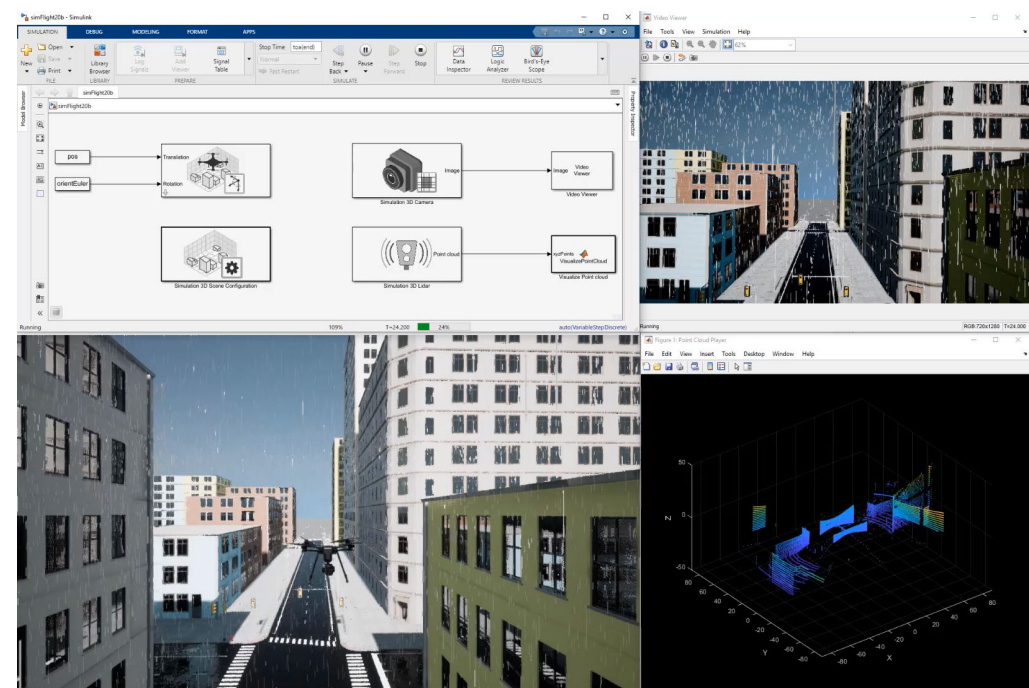
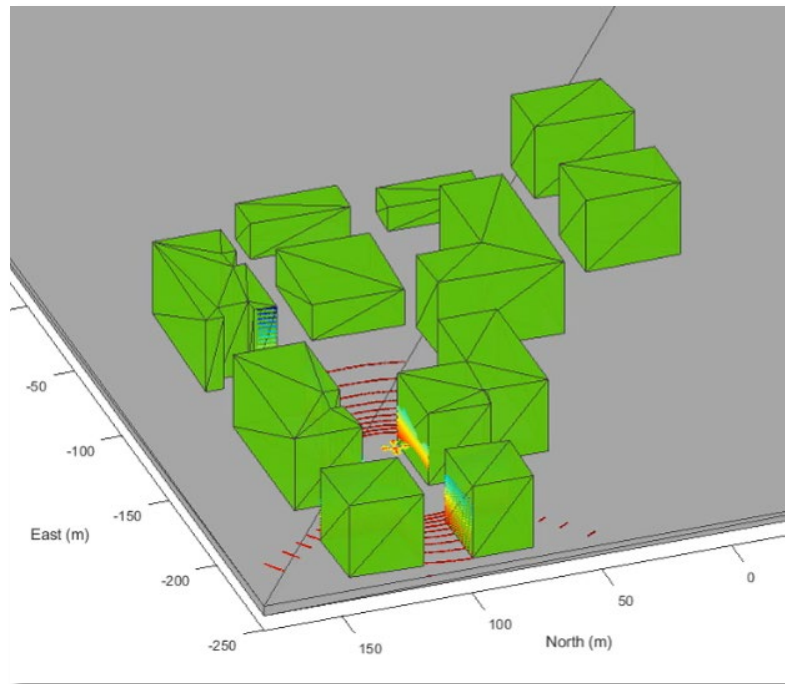
Gust 12 m/s Westward and 9 m/s Upward



Generate Sensor Data with Scenario Models

Cuboid
Lower Fidelity

Unreal Engine®
High Fidelity



Rapidly author scenarios and generate sensor data

Realistic graphics to test autonomous algorithms in closed-loop simulations

[Link](#)

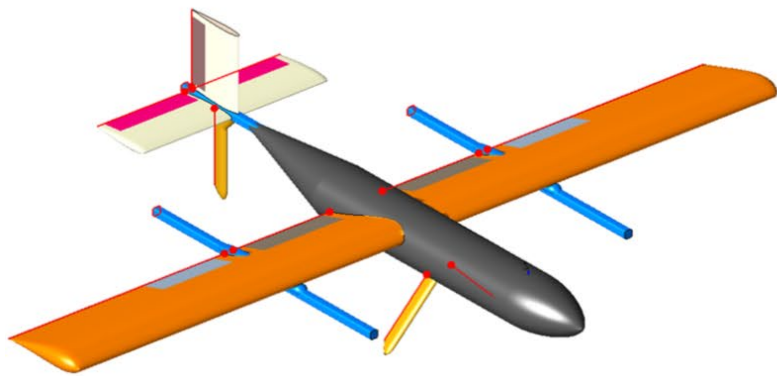
[Link](#)

Cesium Integration Enables Real-World Geography



External Visualization

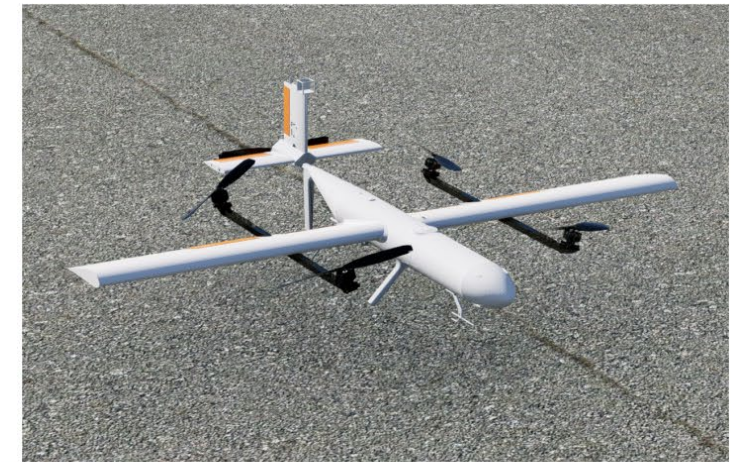
- All simulation models have a **fully-animated** geometry model for external visualization
- **X-Plane 12** is used primarily; all internal flight dynamics are **disabled**
 - UDP communication to and from X-Plane to **override** internal states
 - *datarefs* can be directly written to for:
 - Animating **control effectors**
 - Driving X-Plane **cockpit displays**
 - Driving **motion platforms**
- A **full guide** for animation is provided in a recent NASA TM by Comer, Simmons, and Asper [5]



OpenVSP Model



Blender Model



X-Plane Model

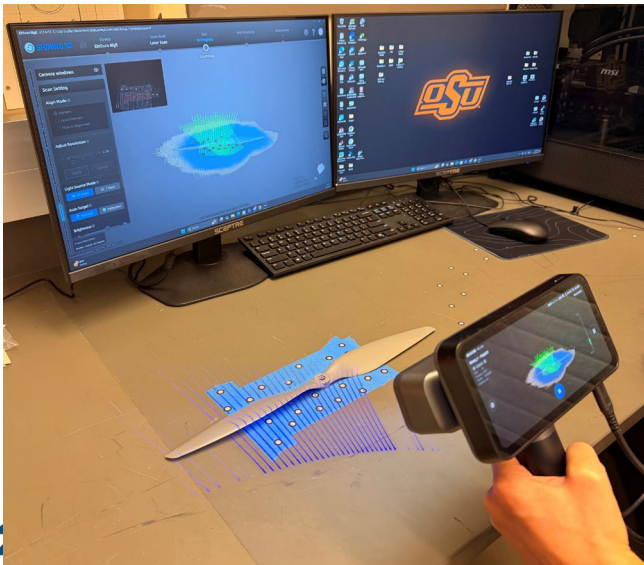
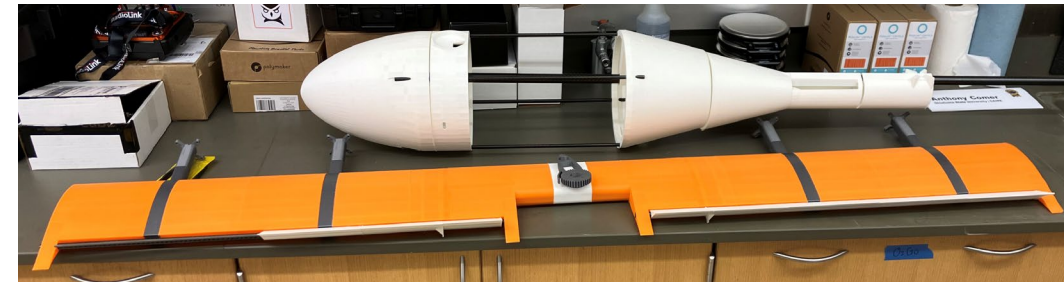
Rapid Prototyping via Additive Manufacturing



- Design for additive manufacturing (DfAM) practices
 - Enables **95%+ 3D-printed airframes**
 - Modular parts for **fast iteration** and build
 - Refined print settings **reduce part weight** while maintaining strength requirements
- S2FAR Lab **printer “farm”** – 10 hobby-grade printers
 - Typical **6-7 ft** wingspan (15-25 lbs) vehicle **printed in 18-24 hrs**
- **3D scanning** of COTS parts for **1:1 CAD** when needed



S2FAR Lab printer “farm” with 7/10 printers shown



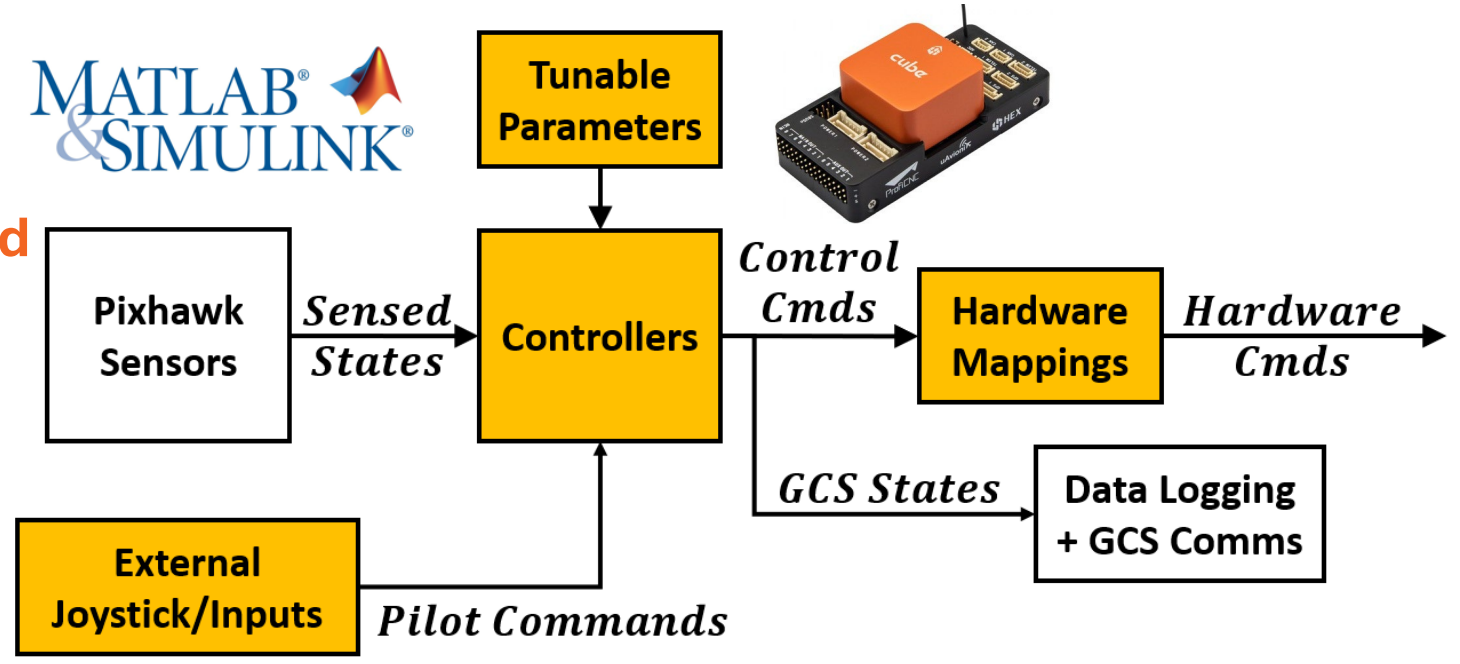
Moment of inertia rig for determining I_{xx} , I_{yy} , I_{zz}

Hardware Implementation – UAV Support Package for PX4



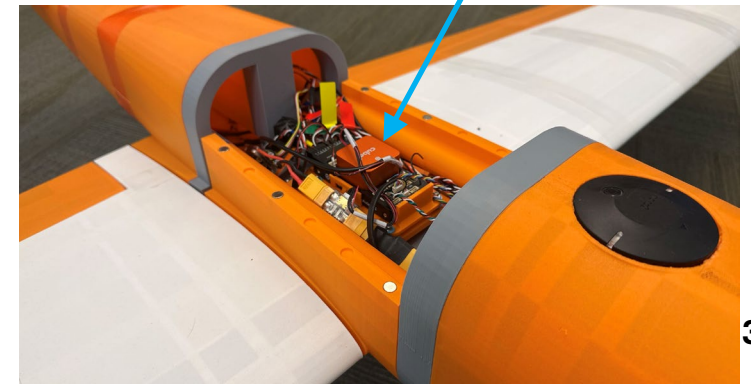
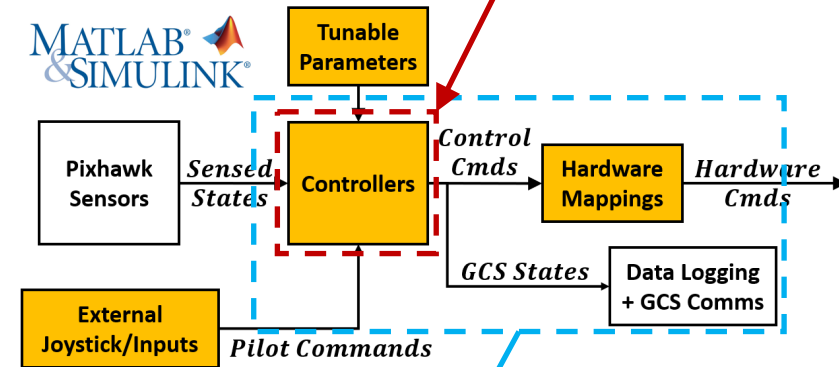
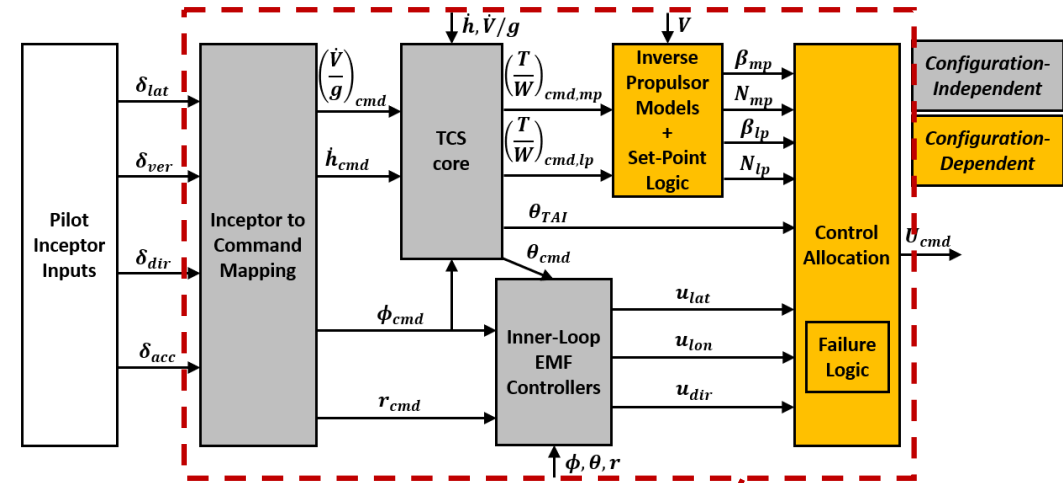
- The VISTA Simulink model is developed to be **hardware-ready** to enable “picture-to-code” using the MATLAB **UAV Support Package for PX4 Autopilots**
- **Modified** PX4 firmware to enable:
 - **Custom** telemetry messages, uORB topics, and drivers
 - Supports flight testing from computer-driven **ground control stations**
 - Internal and external data logging of custom **flight control system states**
 - Integration with **motion platforms** in real time

- Internal PX4 flight controls are **replaced** with custom **Simulink** model code
- Yellow blocks are **identical** to those used in the simulation model
- **Pixhawk** flight controller hardware



Hardware-Ready, Practical Control Law Development

- Rapid control-law development:** tuned quickly in simulation and kept hardware-ready from the start
- Generalized VTOL control architecture:** validated across dissimilar configurations with flight test
- Practical implementation constraints:** minimal state feedback, real-time execution on Pixhawk-class hardware
- Flexible model:** we can develop controls in-house or evaluate externally-provided control laws in our workflow



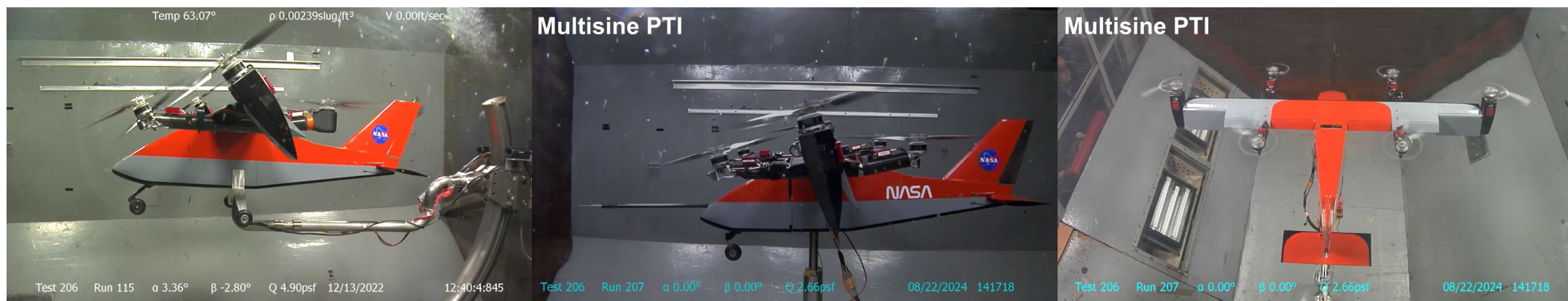
NASA Langley develops a Process to Quickly Deploy Custom Control Laws to Aircraft

NTRS - NASA Technical Reports Server

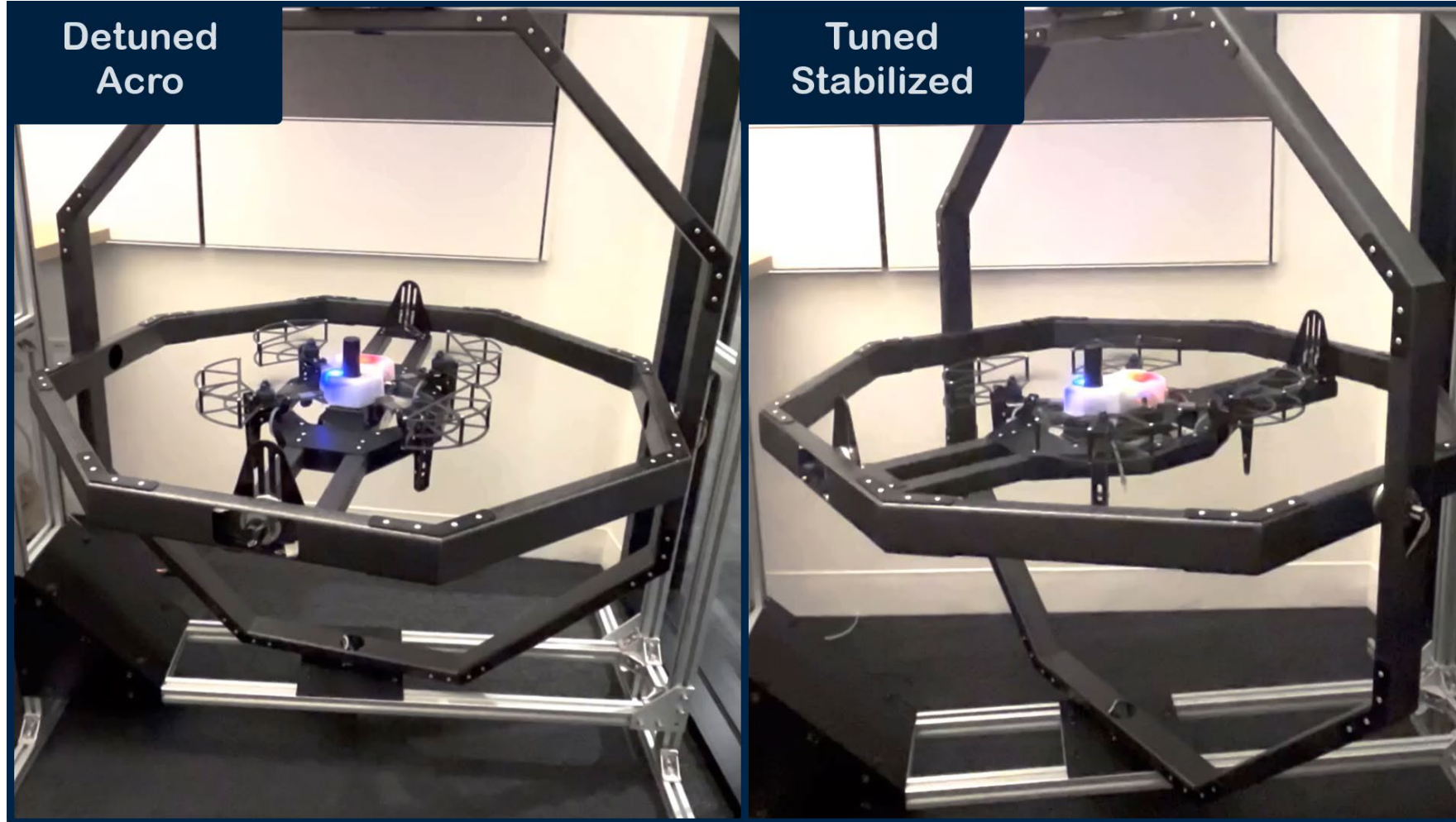
- Rapid Flight Control Law Deployment and Testing Framework for Subscale VTOL Aircraft
 - <https://ntrs.nasa.gov/citations/20220011570>
- Inexpensive Multirotor Platform for Advanced Controls Testing (IMPACT): Development, Integration, and Experimentation
 - <https://ntrs.nasa.gov/citations/20240000223>
- Aero-Propulsive Damping Characterization for eVTOL Aircraft Using Free Motion Wind-Tunnel Testing
 - <https://ntrs.nasa.gov/citations/20240016299>
- Design, Simulation, and Flight Testing of a Multi-Purpose VTOL Flight Control System
 - <https://ntrs.nasa.gov/citations/20250000954>

“This solution made it easy to take a simulation-developed control law and implement it onto a flight vehicle. In the past, hardware integration was notoriously difficult. Now we can deploy and test a new flight controller in minutes.”

G. D. Asper, B. M. Simmons, R. M. Axten, and K. A. Ackerman
NASA Langley Research Center

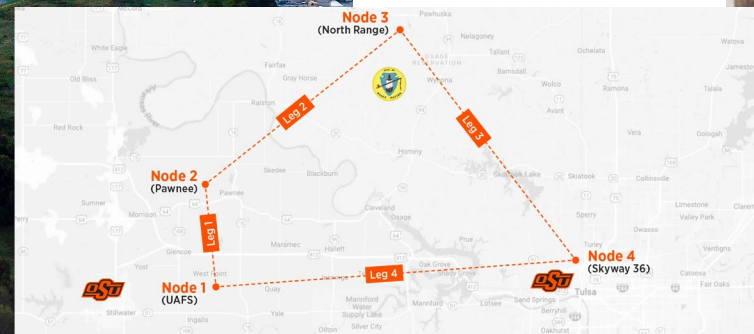
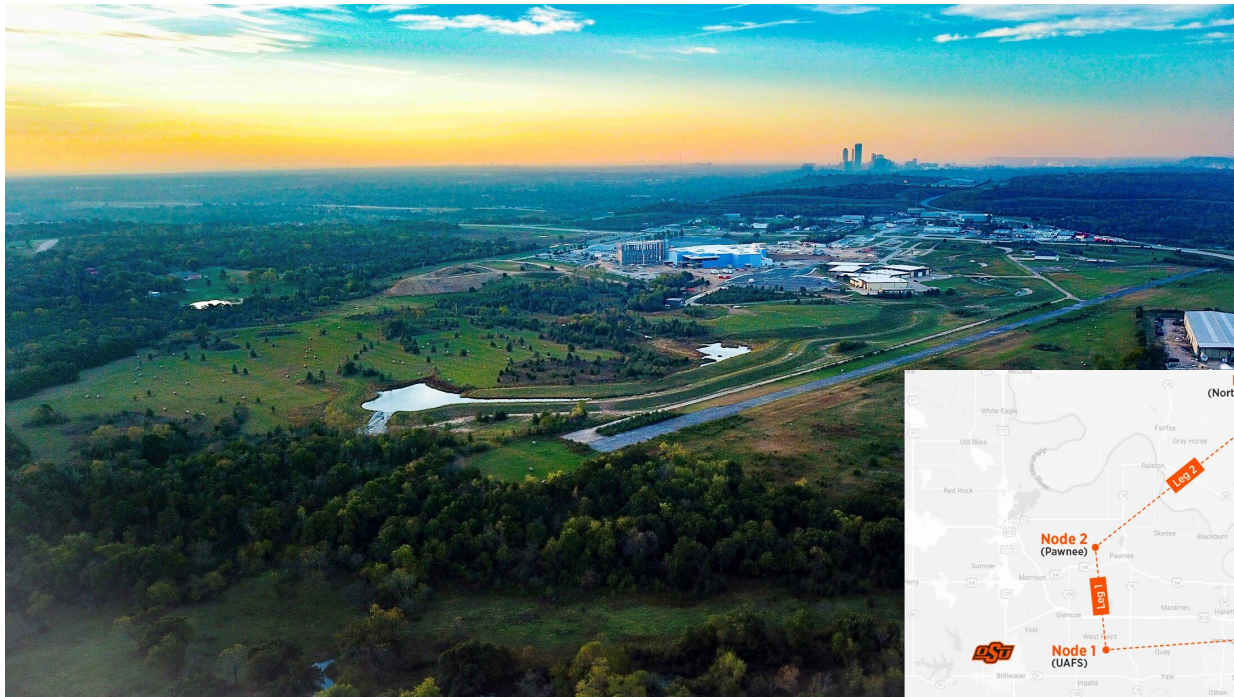
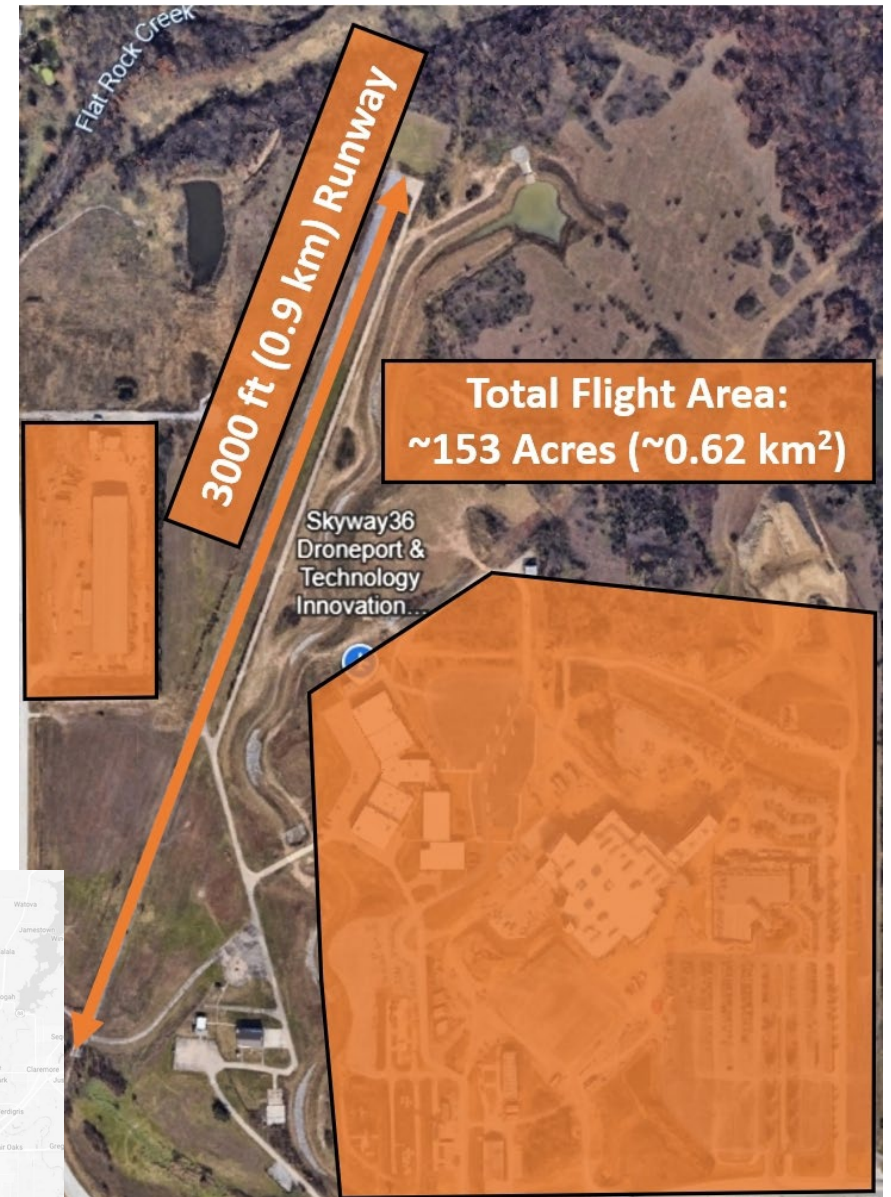


Controller Deployment



Flight Test Site – Skyway 36 Drone Port (Tulsa, OK, USA)

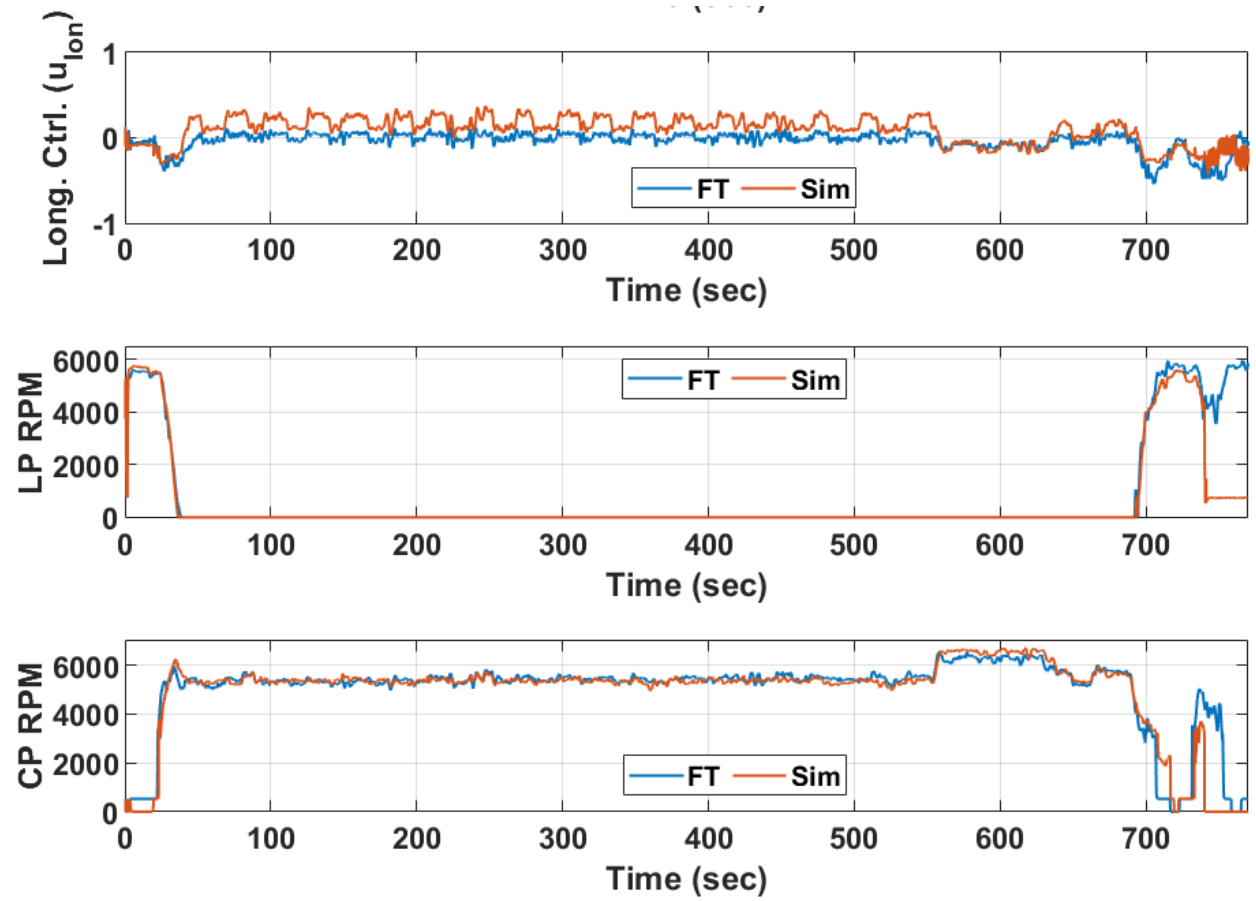
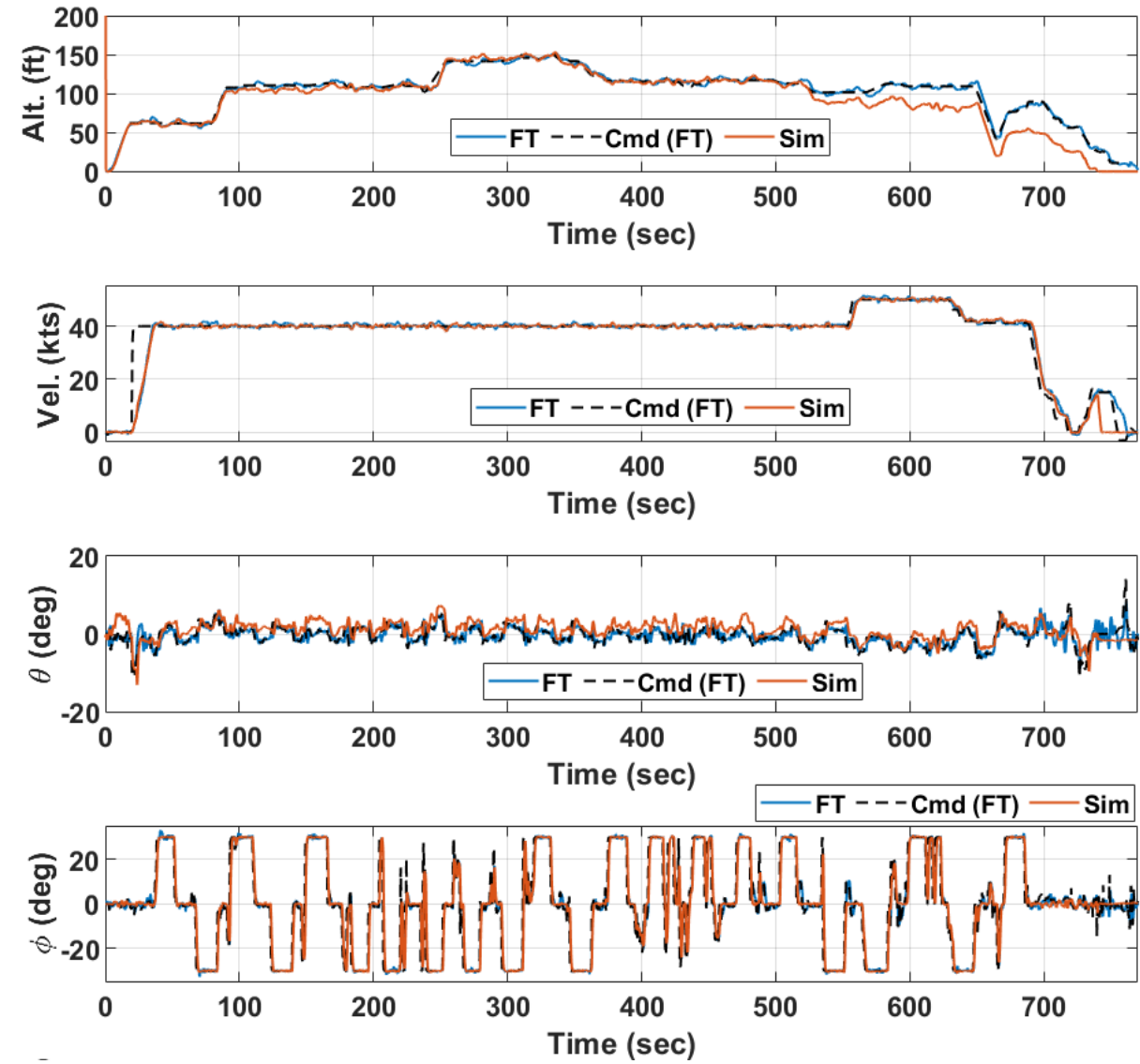
- S2FAR Lab has access to the **Skyway Range** (4 nodes)
- **Skyway 36 Drone Port** is located ~5 miles north of the OSU-Tulsa campus
 - Over **150 acres** of flight area
 - **3000 ft** paved runway
- The **WindShapeUSA** facility is in the same location



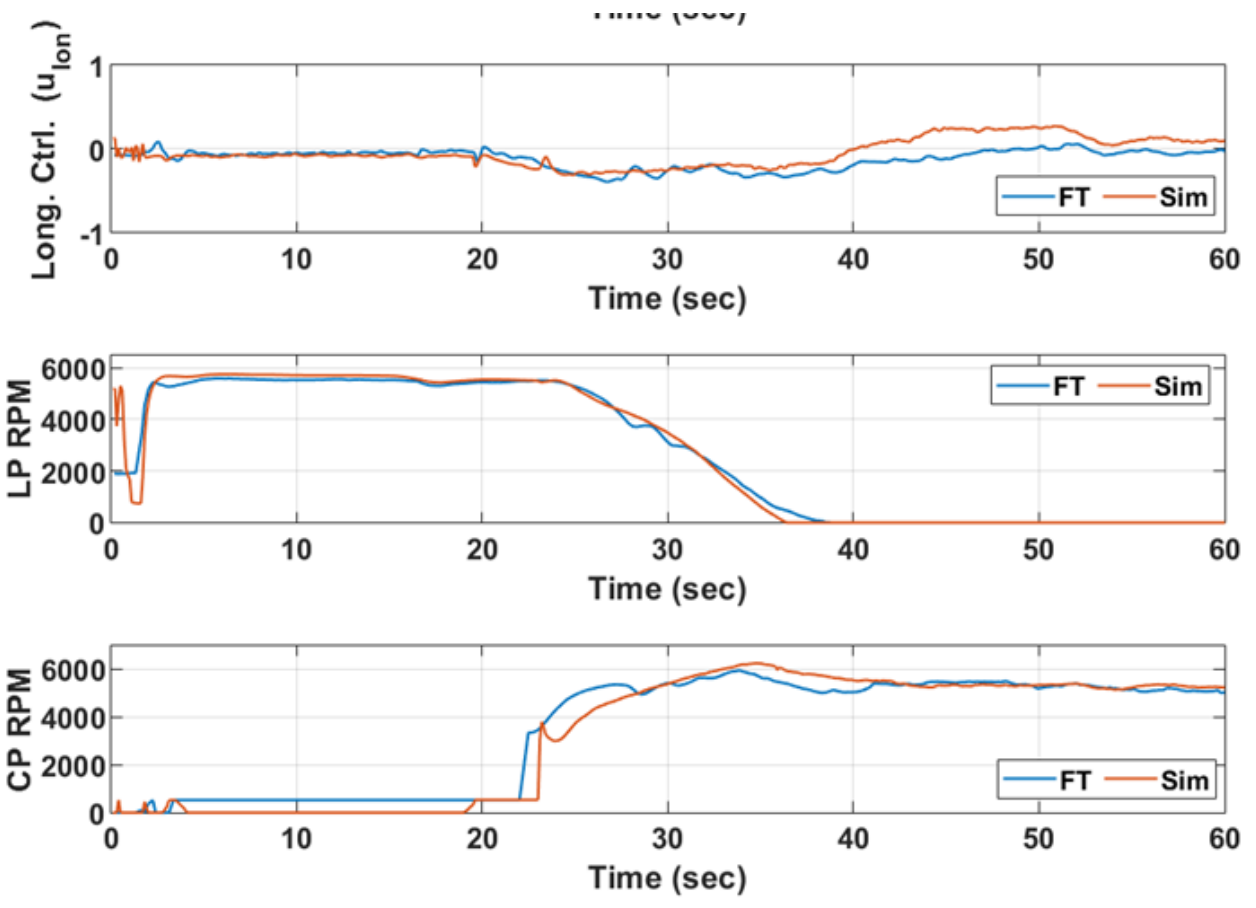
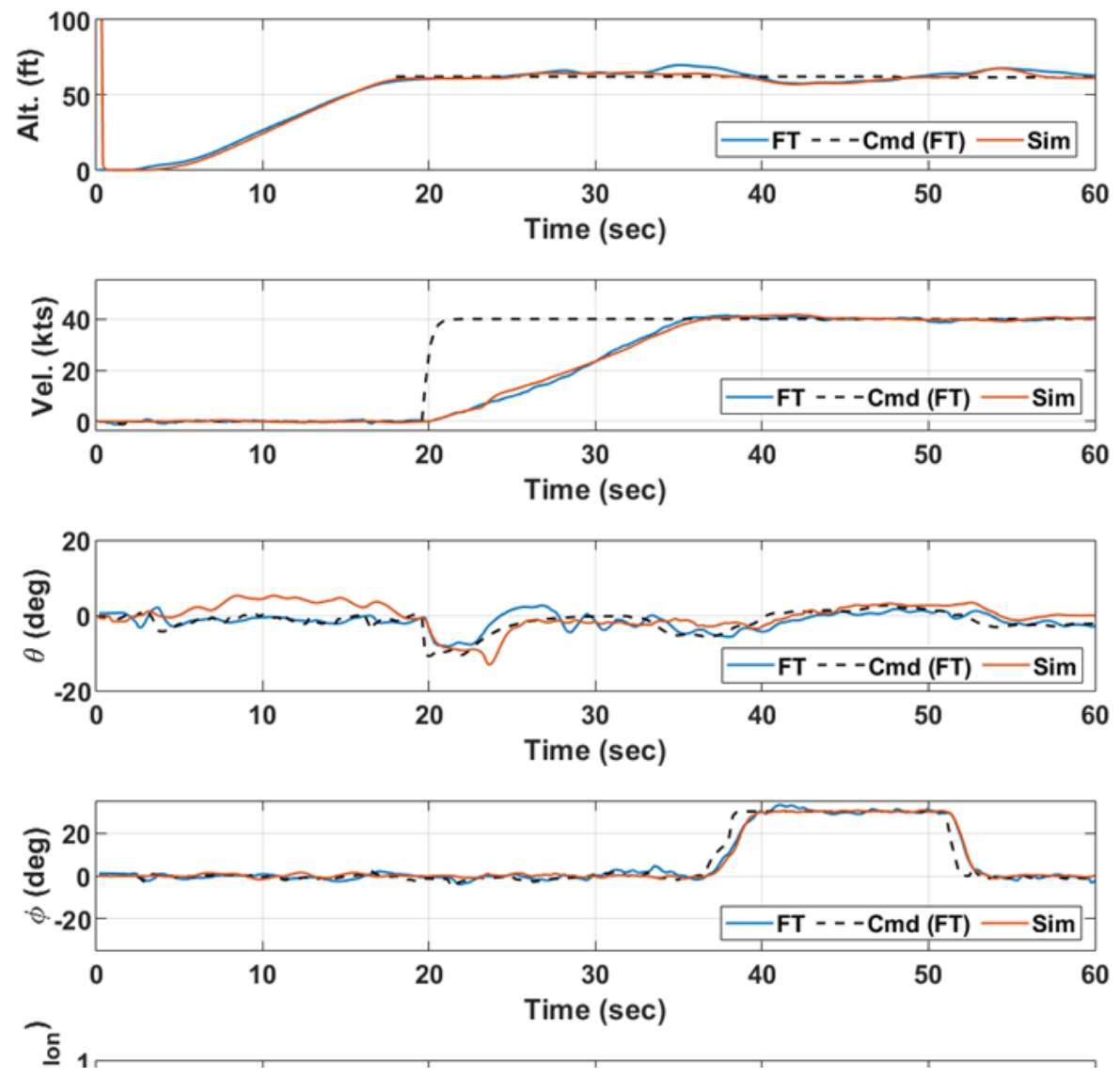
Transition Flight Video – S2F-X200



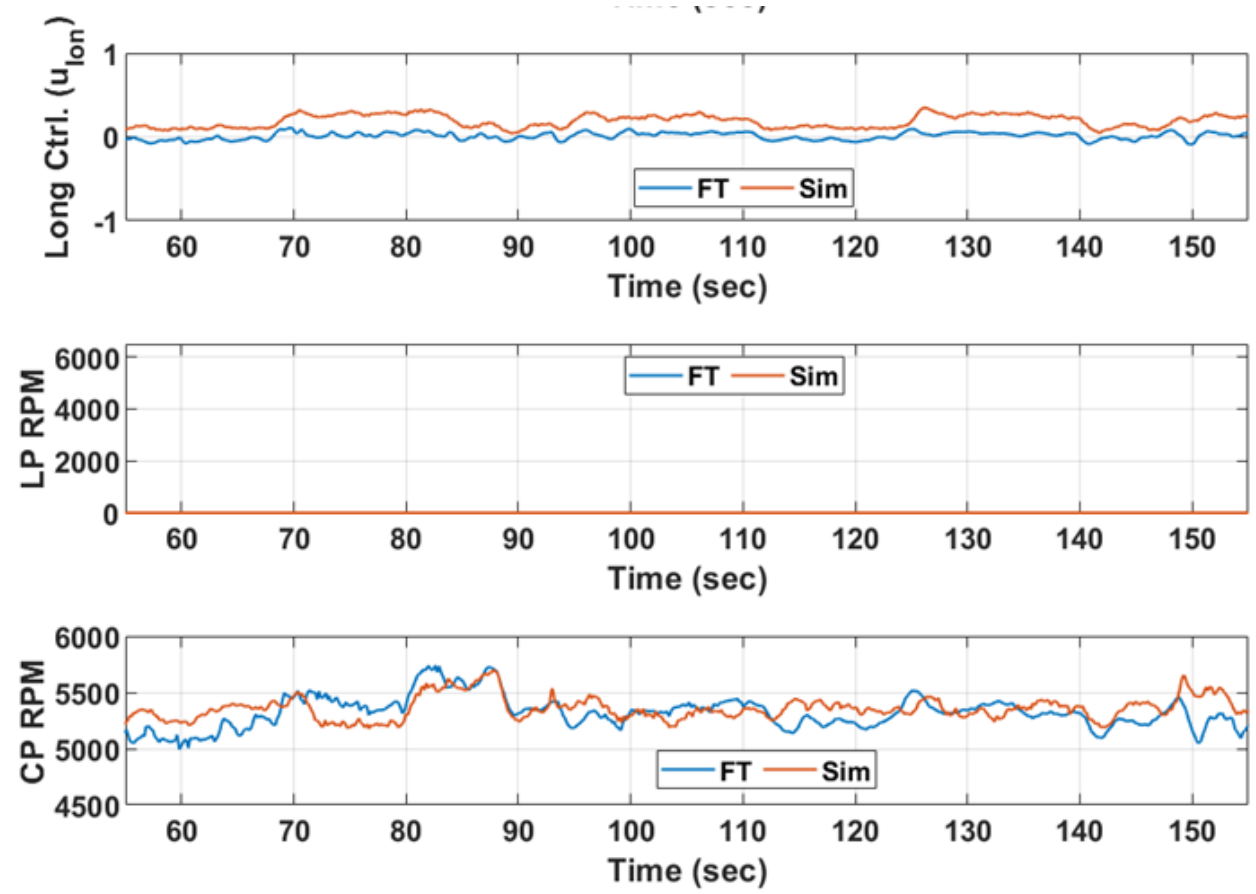
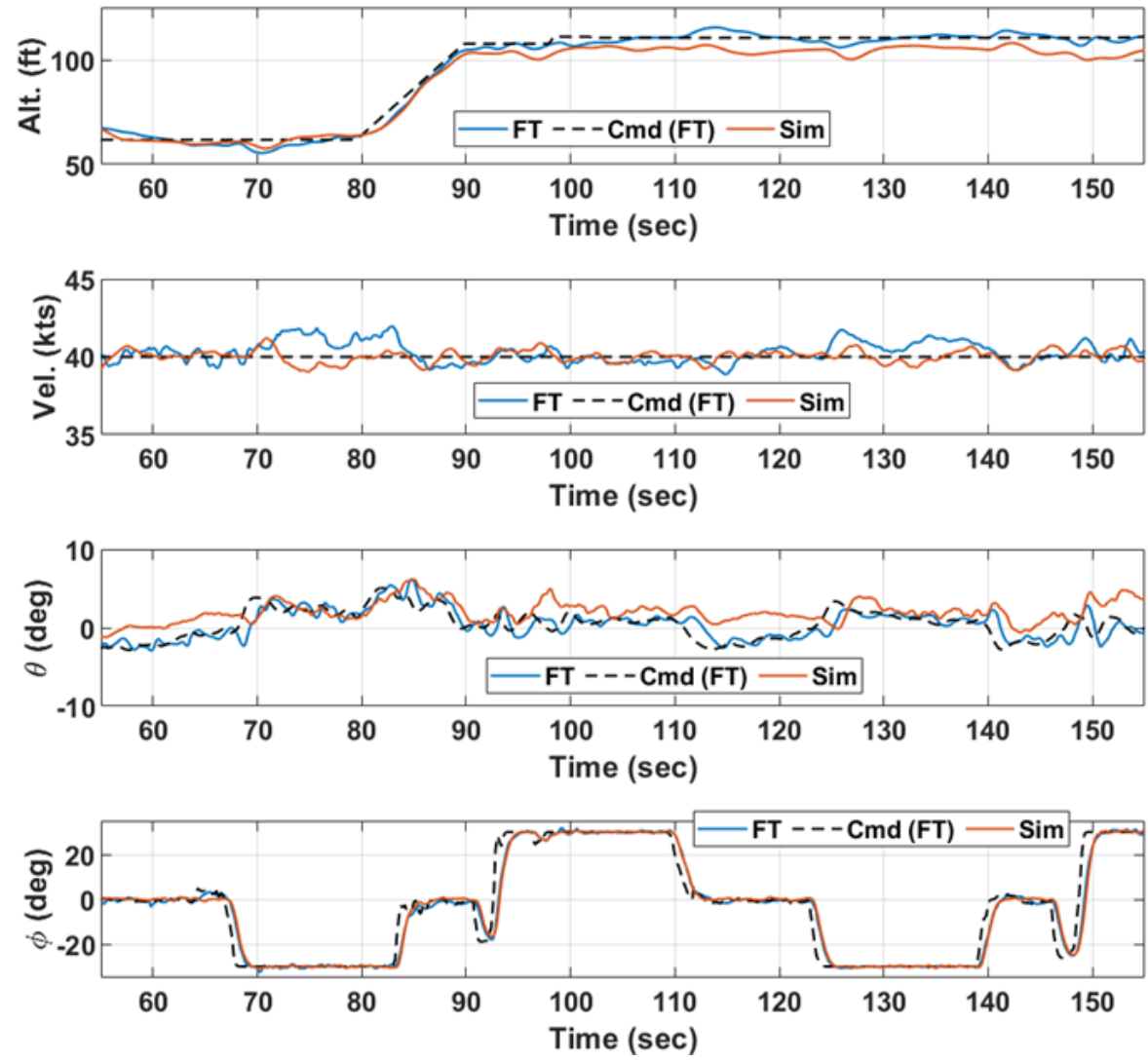
Transition Flight Results – VISTA vs FT



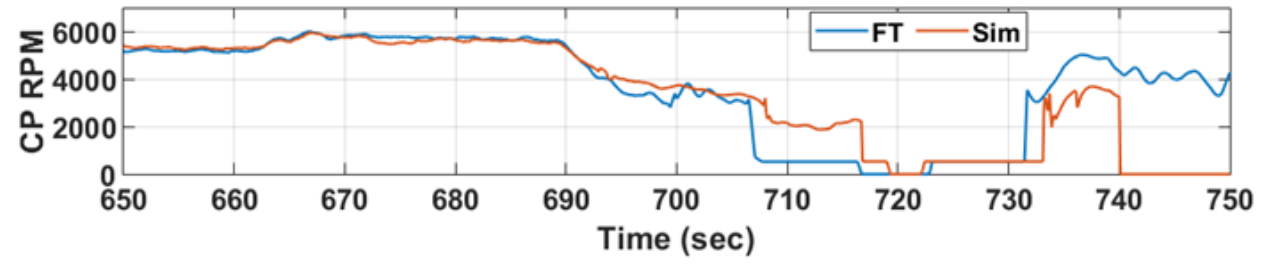
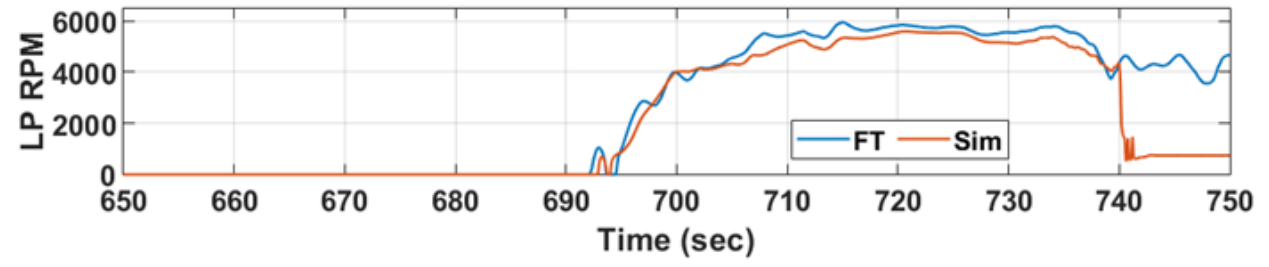
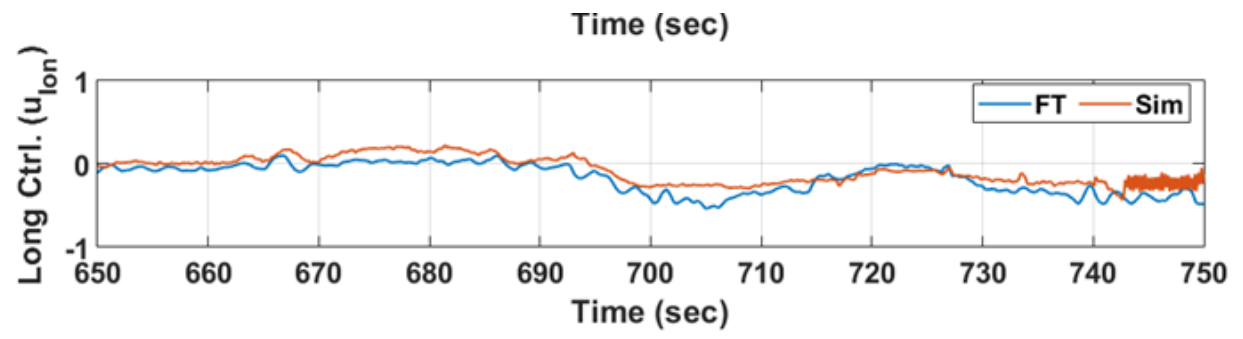
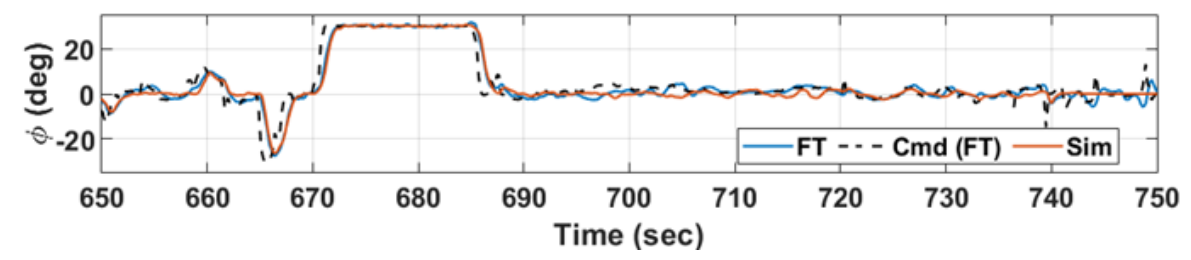
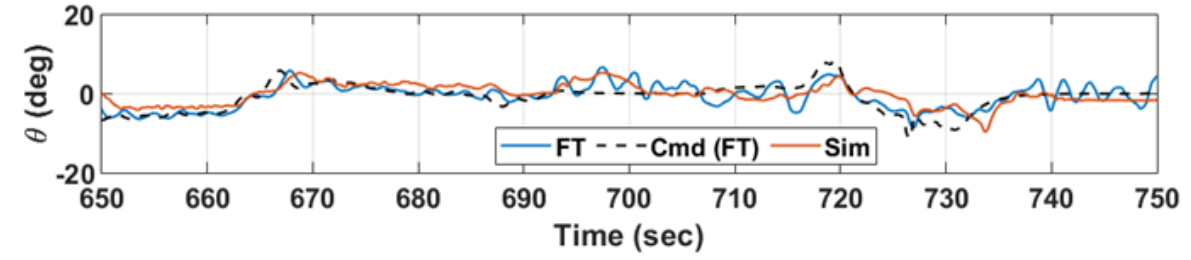
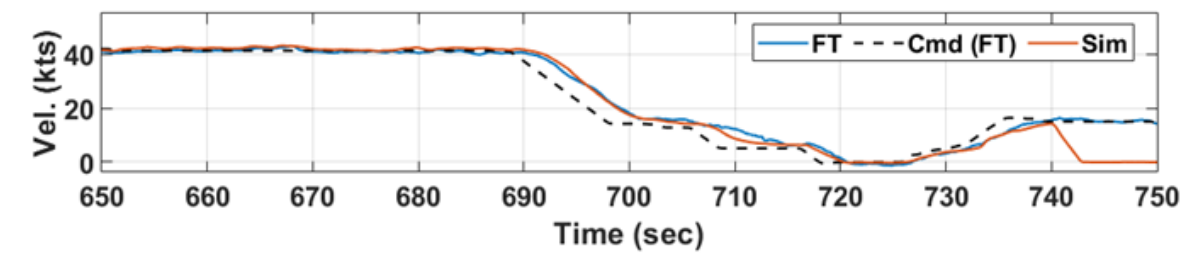
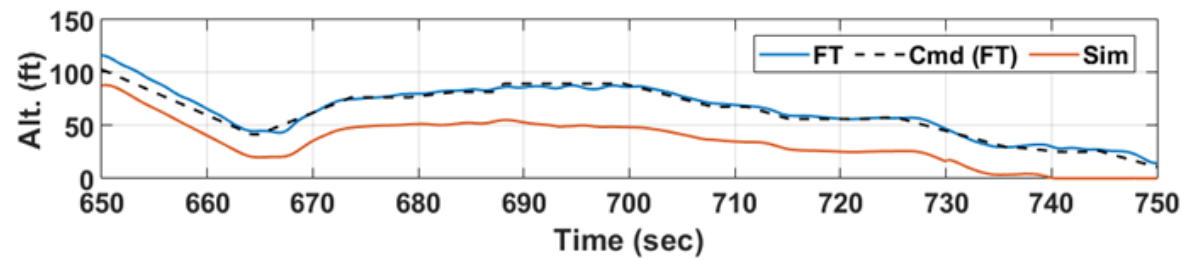
Transition Flight Results – VISTA vs FT (DXN)



Transition Flight Results – VISTA vs FT (FFM)



Transition Flight Results – VISTA vs FT (AXN)



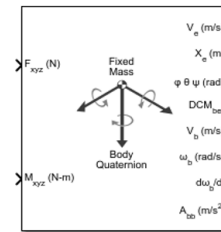
Concluding Remarks

- The Simulation to Flight Applied Research (S2FAR) Laboratory at **Oklahoma State University** has developed a simulation to flight workflow to enable **rapid, inexpensive subscale flight** testing for use in multiple research avenues
 - OpenVSP model to first flight in **2-3 weeks**
- A **lift + cruise** eVTOL **Group 2** UAV was designed, modeled, fabricated, and flight tested through a MATLAB/Simulink-based workflow
- The **VISTA** simulation model, when **pilot inputs** were replayed through the model, showed **good** agreement between state time histories
- The **WindShaper** wind walls and corresponding equipment located at **OSU-Tulsa** enables aeropropulsive model validation and control law development **prior to** flight testing
- OSU is developing the **Skyway Range** flight corridor, with the **Skyway 36 Drone Port** node being the primary flight test facility for the S2FAR Lab

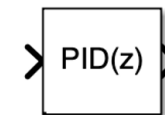
- Current plans include uploading **publicly available** part files, trim data, and linear models alongside structured tutorials for progressing through simple simulation and flight integration

MATLAB and Simulink provide the building blocks for an easily adaptable, modern control design workflow:

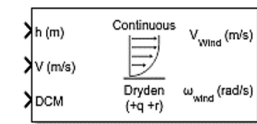
- **Model your platform**
- **Tune your controllers**
- **Virtually test performance**
- **Deploy to Hardware supported by PX4**



Plant Modeling
In Simulink



Control System
Architecture



Modeling Disturbances



UAV Toolbox Support Package for PX4 Autopilots

by [MathWorks Robotics and Autonomous Systems Team](#) **STAFF**

Access PX4 autopilot peripherals with UAV Toolbox and automatically build and deploy flight control algorithms with Embedded Coder

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Thank You! Questions?

Website



Flight Videos

