Artificial Intelligence Flight Tests Using the Learjet Variable Stability System

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412TW-PA-22067: Approved for public release Distribution Statement A: distribution is unlimited.

Overview

- Test Management Project (TMP) Introduction
  - Student TMPs
  - TMP Research Areas
- “Sandbox” for Rapid Experimentation
- Learjet Variable Stability System
  - System Description
  - Safety Trips
- Overview of AI TMPs
- Have DUDE Example TMP
- Test Safety Risk Management
  - Safety Designed into Process
  - Agility in the Safety Process

Test Management Project (TMP)

TMP Introduction
- **Student Test Management Projects**
- TMP Research Areas

Sandbox for Rapid Experimentation

Learjet VSS
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Overview of AI TMPs

Have DUDE Example TMP

Test Safety Risk Management
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- **Real world flight test program**
  - **Customer who provides system under test**
  - **TPS provides flight test and student/staff labor**
  - **Instructors don't have the "right" answer**
- **Part of USAF TPS Curriculum**
  - **~8 months from assignment to final report**
  - **4x student teams per class with staff advisors**
  - **Students are coached through Planning, Executing, Analyzing, and Reporting**
  - **Limited two-week test execution window**
  - **Students deliver written test report and oral presentation as graduation requirement**

TMP Research Areas

TMP Introduction
- Student Test Management Projects
- **TMP Research Areas**

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Have DUDE Example TMP

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- **TPS Research Division focuses resources and curriculum toward specific research topics**

- **Subset of past and present research topics:**
  - **Automatic ground collision avoidance**
  - **Adaptive flight controls**
  - **Alternative position, navigation, and timing**
  - **Advanced mission systems and sensors**
  - **Artificial intelligence**

- **Goal is to position TPS at the interface of SMEs (AI developers), flight testers, and the warfighter**

"Sandbox" for Rapid Experimentation

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Have DUDE Example TMP

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"Deliver performance at the speed of relevance"

-2018 NDS

- **TPS at the interface between:**
  - **SMEs (AI developers, industry, universities, labs)**
  - **Flight Test (experienced staff and AFTC resources)**
  - **Warfighter (students from CAF)**
- **Flight Test Assets:**
  - **Learjet and X-62A VISTA (Variable Stability System)**
  - **Instrumented F-16s and T-38s (real-time TM and post-flight data)**
  - **Datalinks and data access (CMDL and IADS)**
- **Culture of Innovation and Experimentation**
  - **Teach and demonstrate within TPS curriculum**

LL1: Create "sandboxes" for experimentation and innovation.

LJ VSS as a Sandbox

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- **Variable Stability System (VSS) started as a "sandbox" to test flight control systems**
- **Repurposed as a ready-made AI flight test "sandbox"**
- **<u>Agent is directly controlling aircraft through the VSS</u>**

Subset of automatic safety trips and safety pilot oversight:

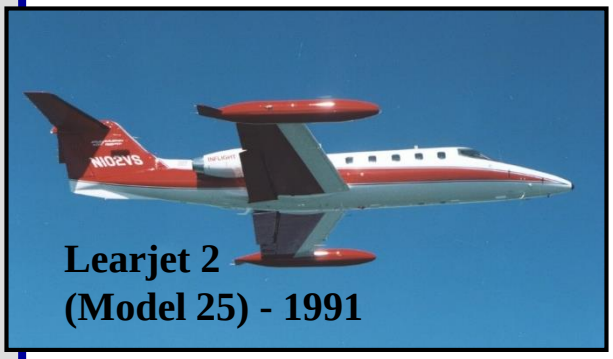
Parameter	Aircraft Limit	Auto Safety Trip
Max Airspeed	359 KIAS/0.82M	
Max Altitude	41,000ft MSL	
Engine RPM	101.2%	
Load Factor (Nz)	-1.0 to +4.0 G	+0.25 to +2.8 G
Max AoA		-1° to +12°
Max AoSS		+/- 10°

***Additional limits exist for roll/pitch rates and control surface deflections/rates**

Learjets

Learjet 1
(Model 24) - 1981

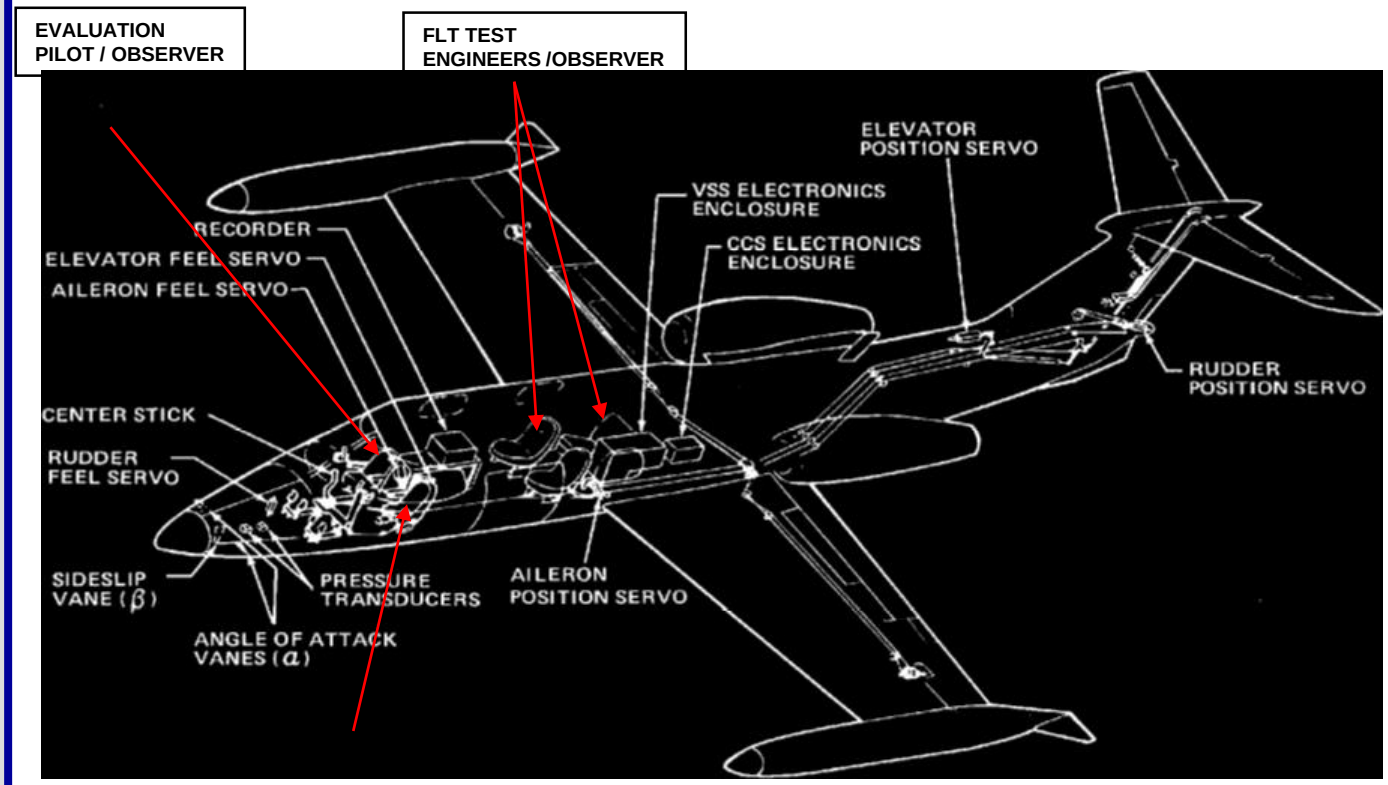
Learjet 3
(Model 25) - 2007



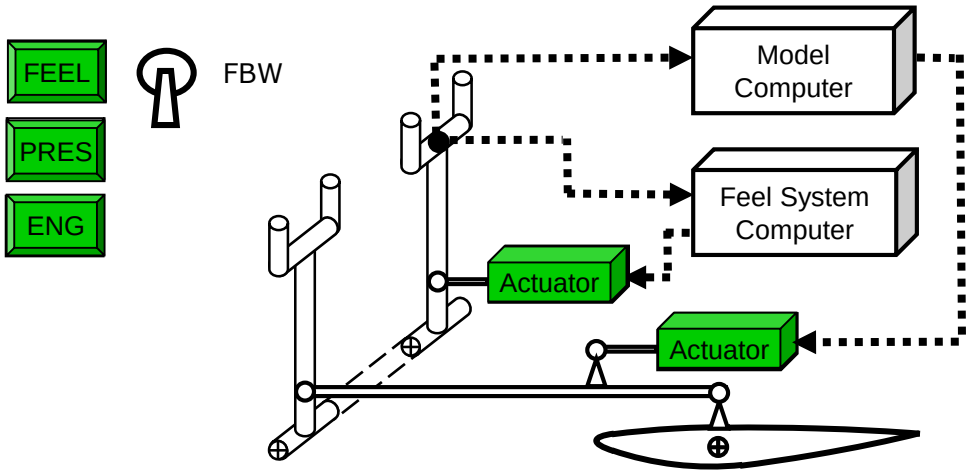
Learjet 2
(Model 25) - 1991

Learjet 4
(Model 25) – (2006) 2015

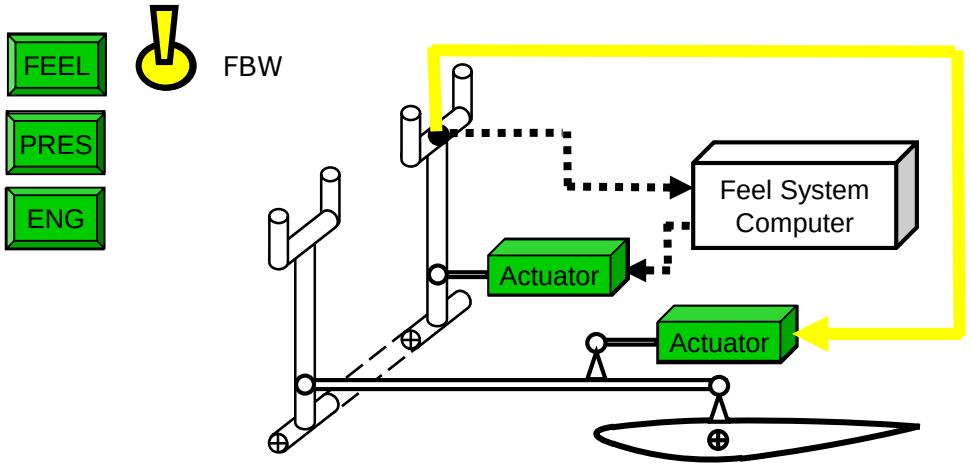
Learjet VSS System Components Overview



VSS Operation

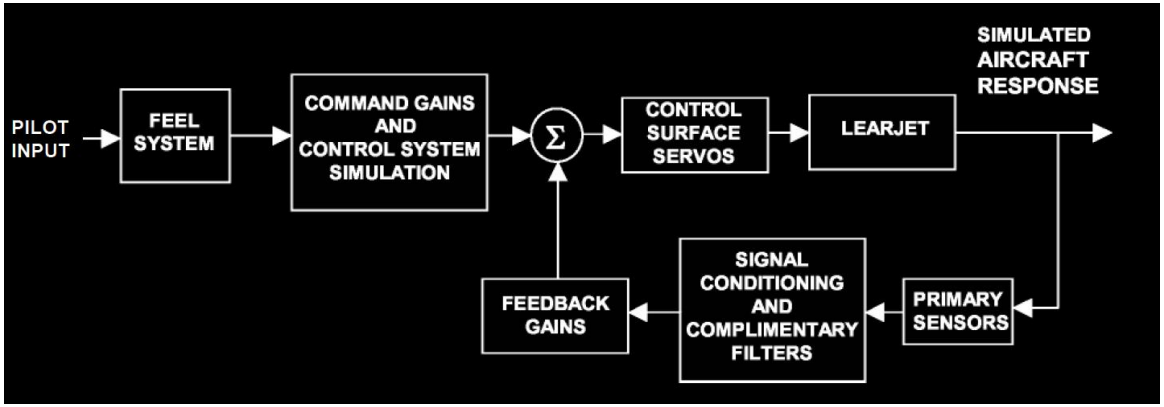


VSS Operation

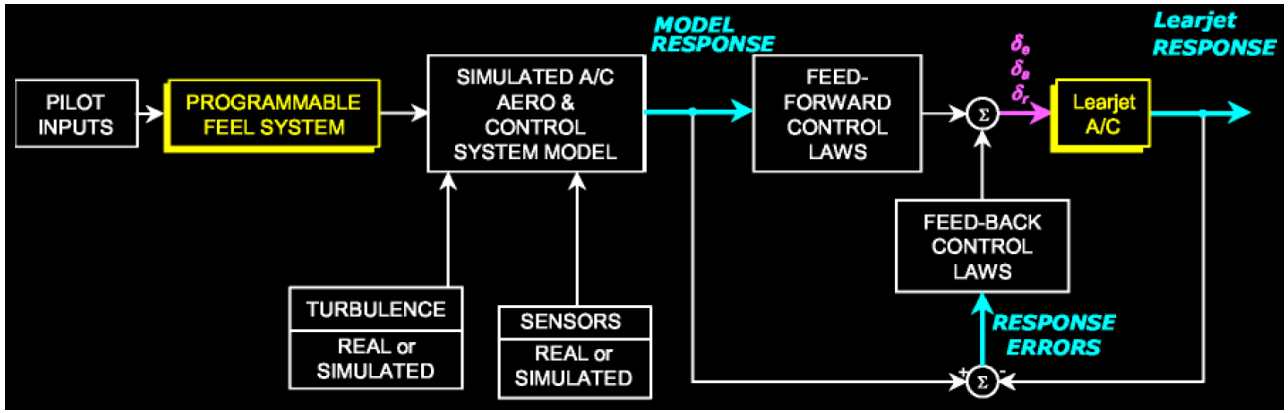


Learjet VSS Schemes

Response Feedback



Model-Following



VSS Modes of Operation

- Basic Learjet
  - Manual control by left seat Calspan safety pilot
  - Retains production Learjet reversible controls, mechanically connected to surfaces
  - Safety pilot flies the aircraft when the VSS is disengaged
- VSS
  - Aircraft controlled by VSS driving surface actuators
  - Control by right seat evaluation pilot or autonomous control from external computer
  - Safety trip system enabled
- Backup Fly-By-Wire
  - Enables evaluation pilot to fly Learjet home if safety pilot incapacitated
  - Reduced VSS mode using fixed gains with basic Learjet characteristics optimized for landing
  - Safety trip system disabled

Learjet Safety Trip System

- Automatic safety trips
  - Preset threshold level and persistence
  - Keeps aircraft dynamic response well within actual airframe limitations
  - Surface hardover protection
  - System failures
- Manual safety trips initiated by either pilot
- Trip results in VSS disengagement
  - Control surface and feel actuators are disengaged by removing hydraulic pressure
  - Control of aircraft immediately reverts to safety pilot
  - Accompanied by aural and visual cues in the cockpit

Learjet Safety Trip System

- Safety Trip Initiated when any of the below thresholds is exceeded
- Protection on Servos
  - Surface servo errors — ±2° (δ_e) ±6° (δ_a, δ_r), 10 ms
  - Surface servo differential pressure — ±850 psi, 10 ms
  - Throttle servo errors — ± 1.7°, 100 ms
  - Throttle differential — 25.3°, 100 ms
  - Feel system servo errors — ±0.5 in (stick) ±0.25 in (pedals), 20 ms
- Protection on Flight Condition
  - Lateral load factor (n_y) — ±0.3g, 20 ms
  - Normal load factor (n_z) — +0.25g to +2.8g, 20 ms
  - Angle of attack — -5° to +12°, 20 ms
  - Top tail rolling moment — ±7900 ft-lb, 20 ms
- System Monitoring
  - NGC computer heartbeat — discrete, 120 ms
  - NGC computer safety trips — discrete, 0 ms
  - Low hydraulic fluid level — discrete, 0 ms
  - Attitude gyro flag — discrete, 40 ms
  - Autopilot/yaw damper engaged — discrete, 0 ms

Manual VSS Disengage Buttons in Cockpit

Backup FBW Mode

- In the unusual circumstance that the safety pilot is incapacitated or a safety pilot control cable breaks, the aircraft can be flown by the evaluation pilot by engaging the FBW mode
- The feel and control surface system gains are fixed and optimized for landing configuration
- The handling characteristics are basic Learjet with yaw damper ON
  - No aircraft state feedback is used (except for yaw damping)
- Safety trip system is disabled (automatic and manual)

Overview of AI TMPs

Have SPIDERS (Class 19B, Mar 2020)

- AI agent attempted to geo-locate emitter and capture image for auto-target recognition
- Agent issued heading guidance to human pilot in F-16D carrying Skunk pod

AFFTRAC (Class 20A, Sep 2020)

- AI agent analyzed ISR imagery to determine optimal flight path to maintain visual custody
- Agent issued heading guidance to human pilots flying MQ-9 and C-12 w/ Sniper pod

Agents act as flight director test points flown by humans

Have Cylon (Class 20B, Mar 2021)

- Six AI agents (surrogate autonomous aircraft) accomplished tasks
- *Agent in direct control* of Learjet 25 w/ Variable Stability System
- Developed infrastructure to fly with constructive (fully sim target), virtual (human in ground sim), and live target aircraft

Agents have direct control of aircraft (with safety trips and safety pilot monitoring)

Have DUDE (Class 21A, Sep 2021)

- Follow on from Have Cylon (6 months is fastest for student TMPs)
- Opportunity for customer, students, and staff to "rapidly" retrain agents and apply lessons learned from previous efforts

Hybrid model for manned/unmanned teaming

Have R2D2 (Class 21B, Mar 2022)

- AI agent (selected from Alpha Dogfight) issues guidance for L-29 BFM while aircrew executes battle management task
- Investigate human trust in AI agents during manned/unmanned teaming

Have DUDE TMP Example

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Overall Test Objective: Demonstrate that an artificial intelligence *agent trained in a simulation could generalize its behavior to the real-world*

- **Specific Test Objective 1: Demonstrate <u>task 1</u> against constructive, virtual, and live aircraft**
- **Specific Test Objective 2: Collect data on agent behavior in a <u>task 2</u> against constructive and virtual targets**

Unfortunately our partners do not want their agents, training, or tasks discussed in a public environment. However, lessons learned are AI agnostic.

<u>Have Cylon/DUDE</u>: First known instance of AI agent controlling full scale aircraft!

LL2: Always look for opportunities to collect more data. You never know when you may be creating the training dataset for the next AI project.

Test Safety Risk Management

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- **All flight test in AFTC is governed by the Test Safety process (AFTCI 91-202)**
- **Defines the process for:**
  - **Identifying and mitigating known hazards**
  - **Independent risk assessment by SMEs**
  - **Assessing and accepting residual risk**
- **Process is constrained to:**
  - **Test unique hazards**
  - **Credible hazards and outcomes**
- **Test safety and airworthiness approval are separate processes**
- **Each project undergoes a technical and safety review by a board of independent experts**
  - **Leverage experience at TPS and experts at ETCTF**

Safety Designed into Process

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- **Have DUDE (21A, Sep 2021) was a second phase of the Have Cylon TMP (20B, Mar 2021)**
  - **Lessons learned (technical, safety, programmatic) were carried forward during test planning**
  - **Agents were retrained by customer**
  - **Aircraft controllers were redesigned by Calspan**

- **Have DUDE Safety Buildup:**
  1. **~50,000 sim runs (per agent iteration) in training**
  2. **Demonstrate task with <u>constructive</u> and <u>virtual</u> aircraft**
  3. **Demonstrate task with <u>live</u> aircraft**

LL3: Emergent behavior is interesting with AI but also brings additional risks. Carefully define the build-up process and ask others to help expose blind spots.

Constructive Scenario

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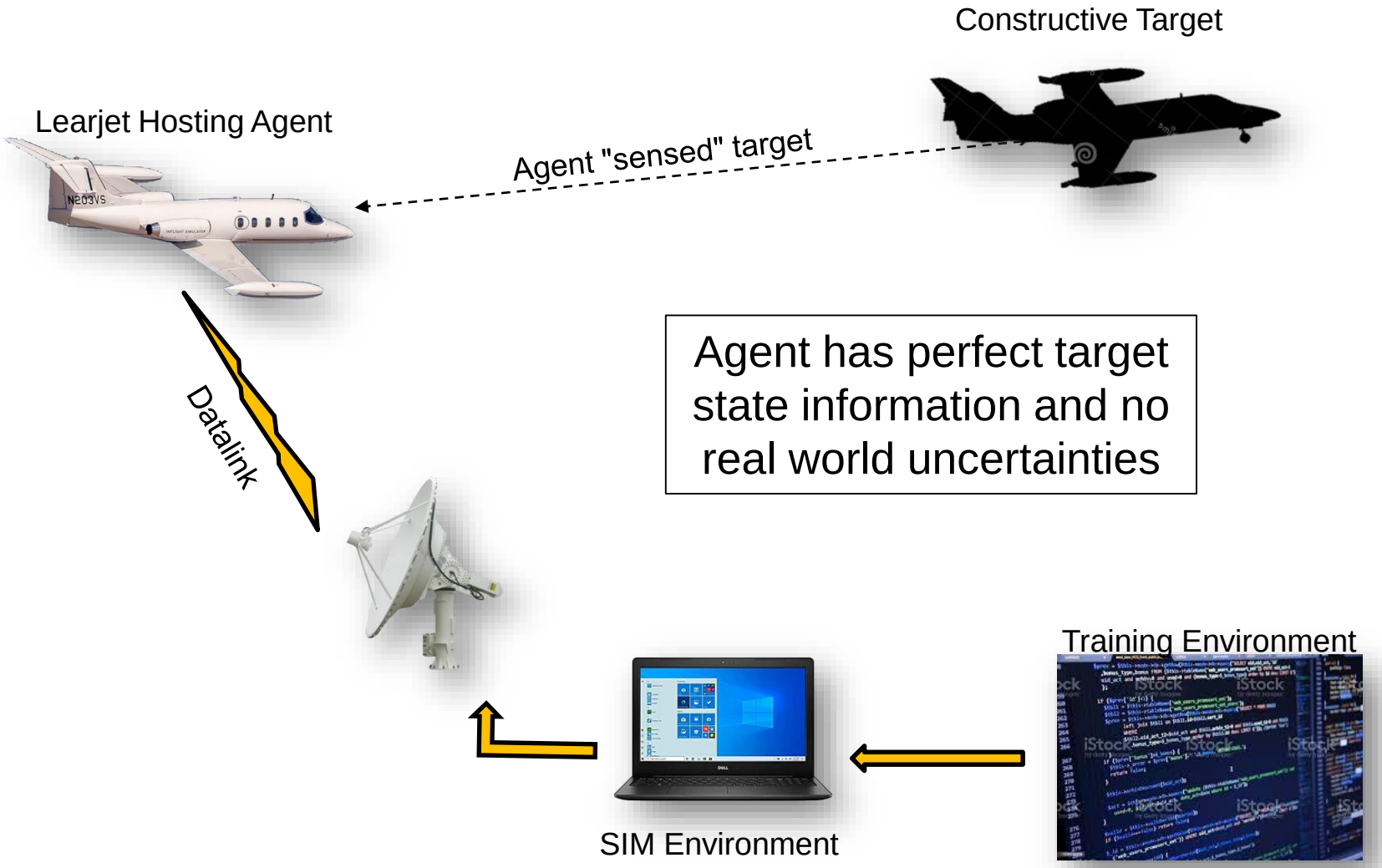

Virtual Scenario

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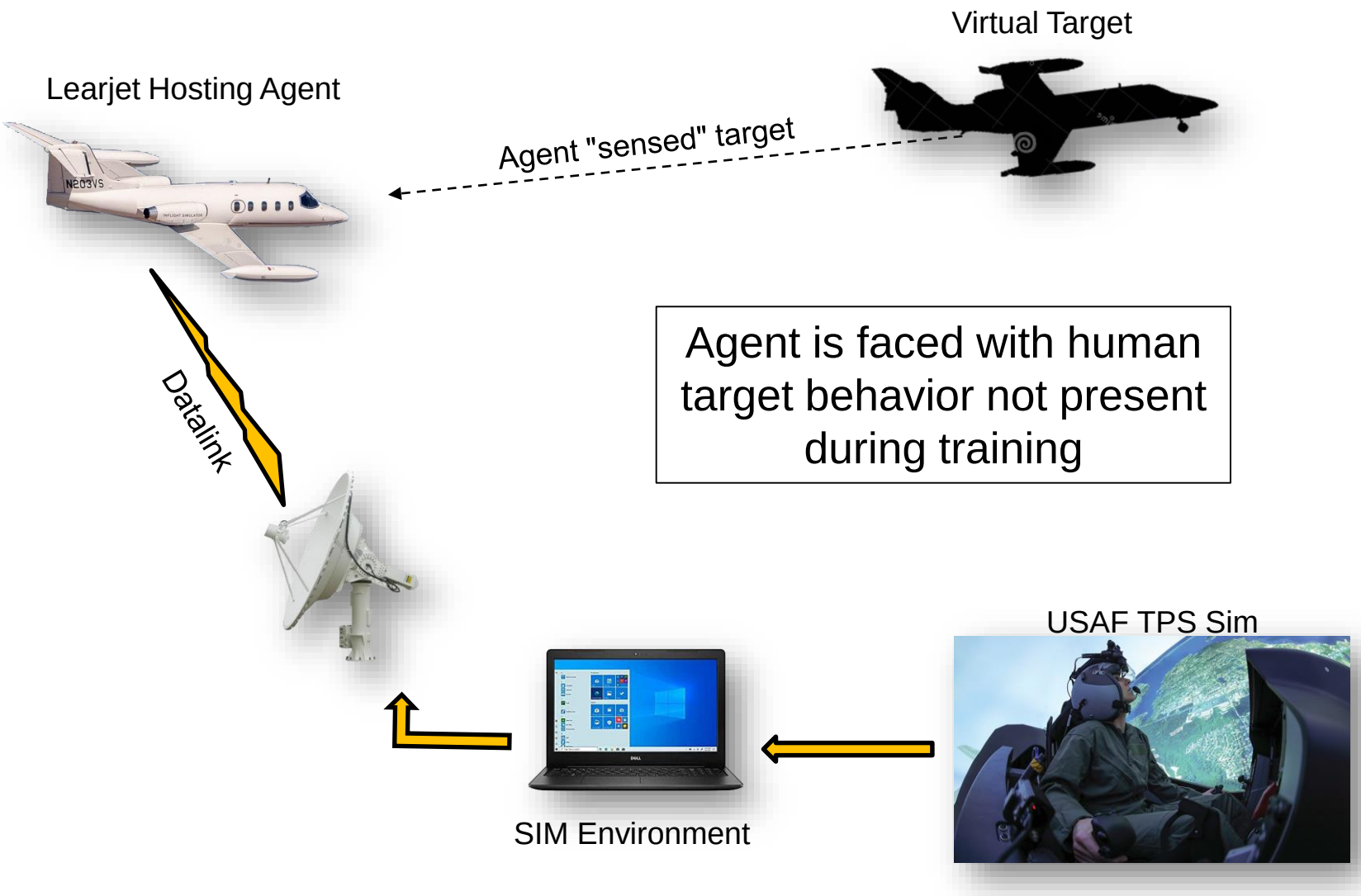

Live Scenario

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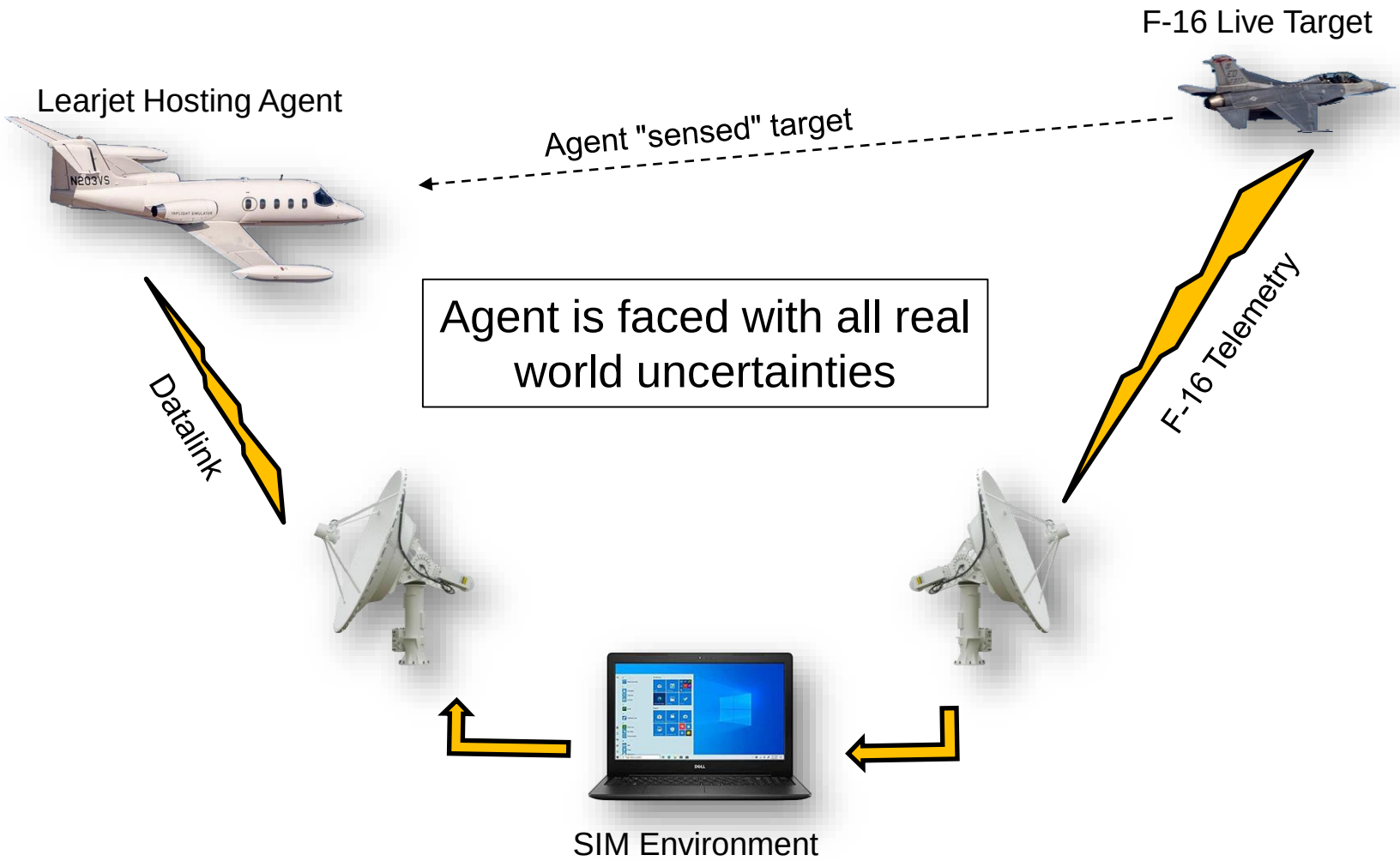

So How'd it Work?

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- **First run:**
  - **Safety Pilot: Mr. Rigel Hebmann, Calspan**
  - **Test Conductor: FUG Lee**
  - **Test Point Duration: 7 minutes, stopped due to lack of desired response**

Agility in the Safety Process

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- **Agility in the Safety Process**

- **Process Agility:**
  - **Customer retrained agent over a weekend**
  - **TPS team worked with TW Test Safety Office to update build-up procedures**
  - **Independent safety review board members consulted**
  - **Change approved by TPS leadership (one business day)**

- **Have DUDE <u>Amended</u> Safety Buildup :**
  1. **~50,000 runs (per agent iteration) in training**
  2. **Demonstrate task in constructive/virtual environments**
  3. **Demonstrate task with live aircraft using altitude offset**
  4. **Demonstrate task with live aircraft**

LL4: Be ready to quickly adapt your plan <u>when</u> you encounter the unexpected. If possible, build backup options into your initial plan.

Success?

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- **Performance improved, more work to be done**

Questions?

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Backup Slides

Challenges to Scale

- TPS is a unique place for this "sandbox" of rapid experimentation
- TPS Vision statement "to be the World's premiere institution for flight test education, training, and research."
  - Curriculum, flight hours, and TMPs included in the recurring annual budget
  - Staff instructors with decades of flight test experience
  - Located at the Center of the Aerospace Testing Universe
- Need additional resources to continue to build on successes
  - More staff, modern systems, aircraft modifications, smart risk acceptance, local leadership empowerment, and delegated approval authority
- Test safety culture meets airworthiness culture
  - Airworthiness culture and process geared toward ensuring system safety of an entire system over its O&M lifetime
  - Test safety culture deals with unique test items operated by specially trained test teams

"A few embers here and there will not bring about the culture change or transform the service's bureaucracy to move faster and with clarity of purpose."

–General CQ Brown

"The current bureaucratic approach, centered on exacting thoroughness and minimizing risk above all else, is proving to be increasingly unresponsive."

-2018 National Defense Strategy

X-62A VISTA

- Continued TPS partnership with AACO, Skyborg, and ACE
- X-62A VISTA brings increased capabilities
  - Replicate the dynamics of desired aircraft (e.g. MQ-20, XQ-58)
  - Safe sandbox to test AI and future autonomy vehicles
    - AI can have control of the aircraft directly or through outer loop guidance within safety envelope
    - Safety pilot overrides and automatic safety trips
- Rapid development
  - 3 months to integrate new autonomous agent or vehicle within VISTA software once upgrade is complete
  - AI will train on same aircraft model simulated by VISTA (minimizing difference between training and flight)
  - Safety pilot eliminates need for extra range resources required by unmanned aircraft