Analysis and Prevention of MCAS-Induced Crashes

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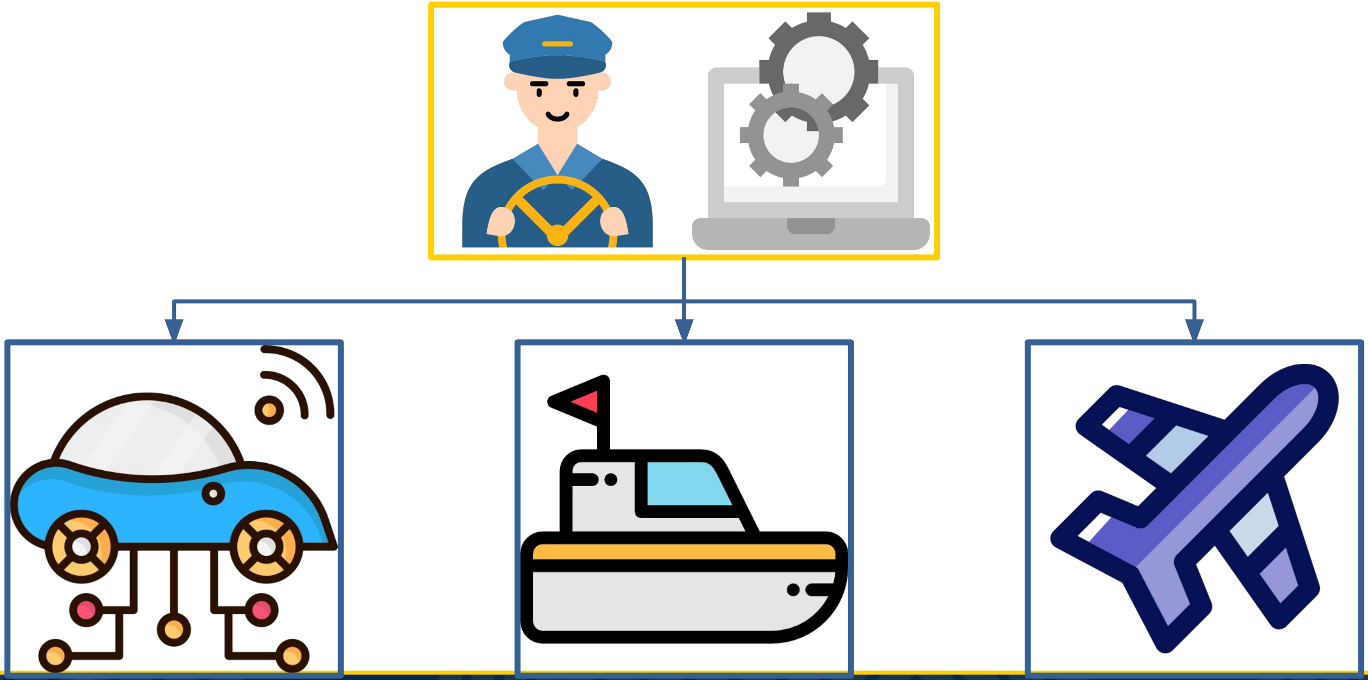
Semi-Autonomous Vehicles (SAVs)



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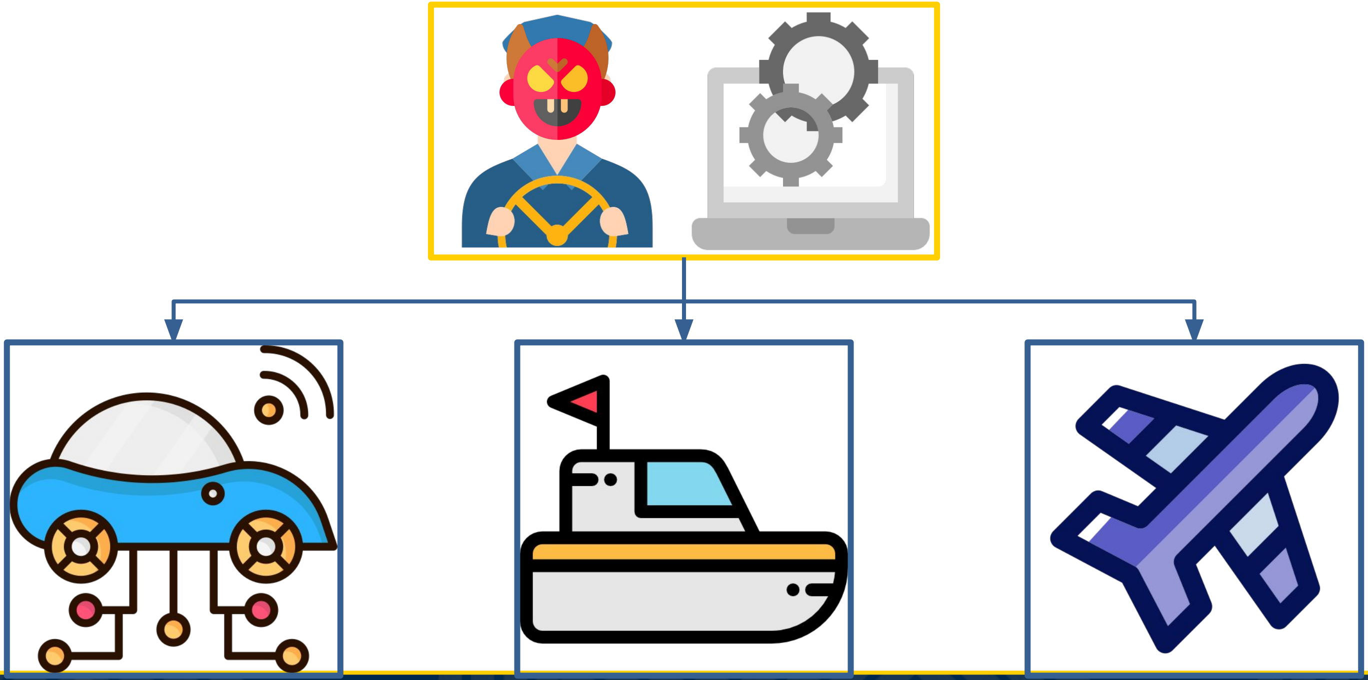

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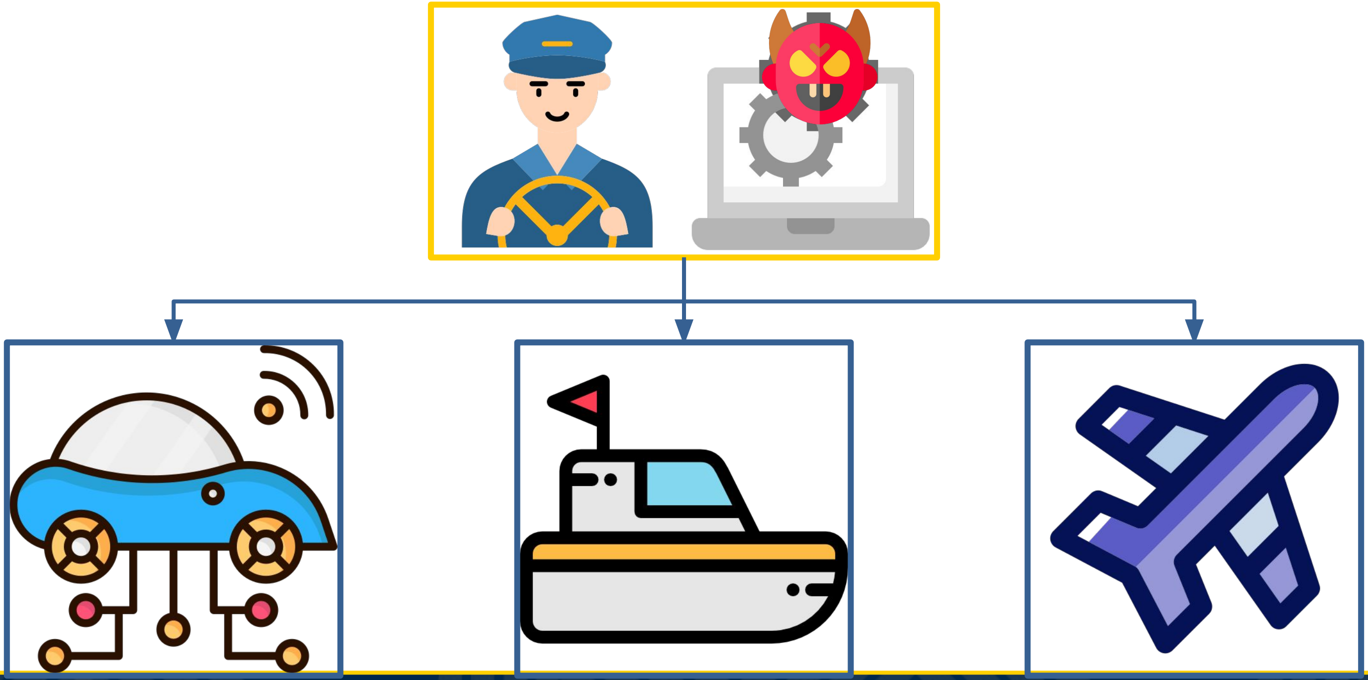
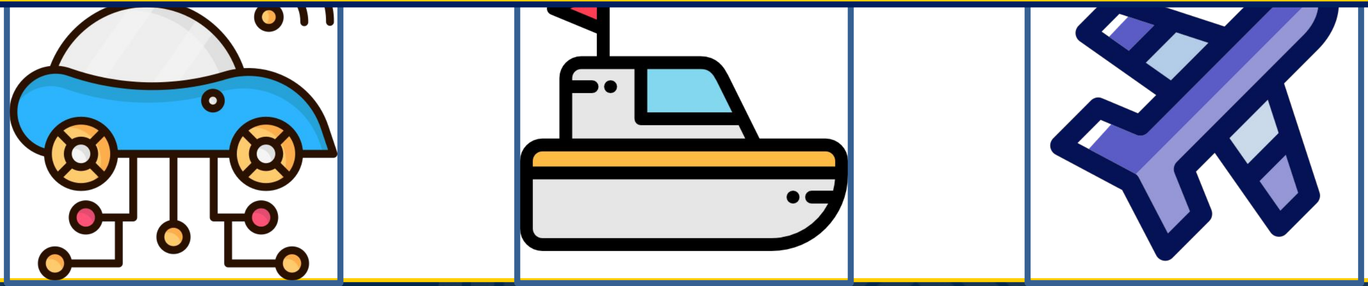


Semi-Autonomous Vehicles (SAVs)

Semi-autonomous systems should not default control to the manual operator or the autonomous controller!



Semi-Autonomous Vehicles (SAVs)

Timeline of Boeing 737-MAX Crashes

2016

Changes During Flight Testing

- Pre-2016: Boeing decides to include MCAS to offset upward pitch due to heavier engines
- March/April 2016: Flight-test pilots discover issue with flight control during low-speed flight conditions
- Sometime after: Boeing gives ~4x greater authority to MCAS… FAA agreed not to notify pilots of the change to MCAS

2017

Aircraft Certification

- March 2017: FAA, EASA certified MAX for flight
- May 2017: First delivery completed

2018

First Crash

- October 2018: Lion Air Flight 610 crashed into the Java Sea

2019

Second Crash and Grounded Aircraft

- March 10, 2019: Ethiopian Airlines Flight 302 crashed into a farm field near Bishoftu, Ethiopia
- March 11-13, 2019: All major countries ground all MAX flights

2020

Return to Service

- January 2020: Issue found with the MCAS system, subsequently fixed
- November 2020: FAA cleared the MAX to return to service
- December 2020: Following repairs, airlines resume passenger service of the MAX

2021

Boeing Settlement and Aftermath

- Early-January 2021: USDOJ charged Boeing with fraud, settled for $2.5B
- Late-January 2021: EASA and Transport Canada cleared MAX with additional requirements
- December 2021: China becomes one of last major countries clear the MAX

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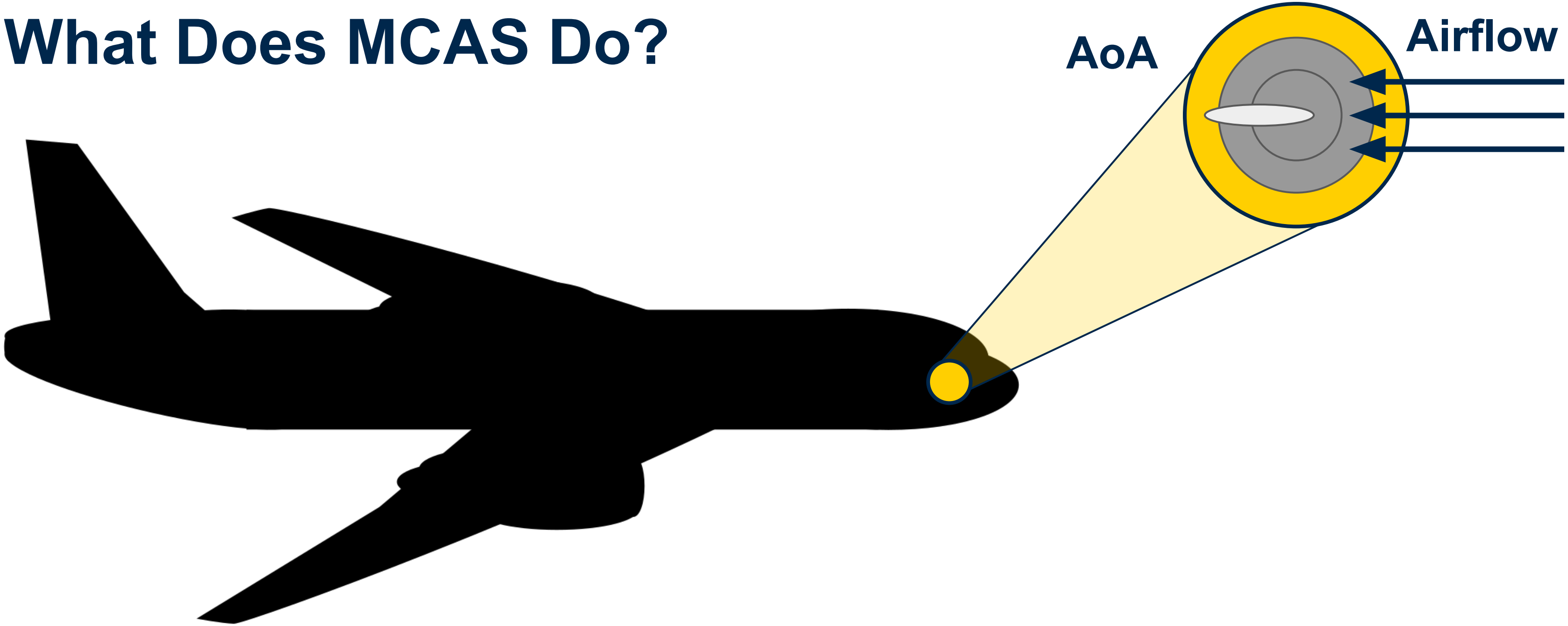

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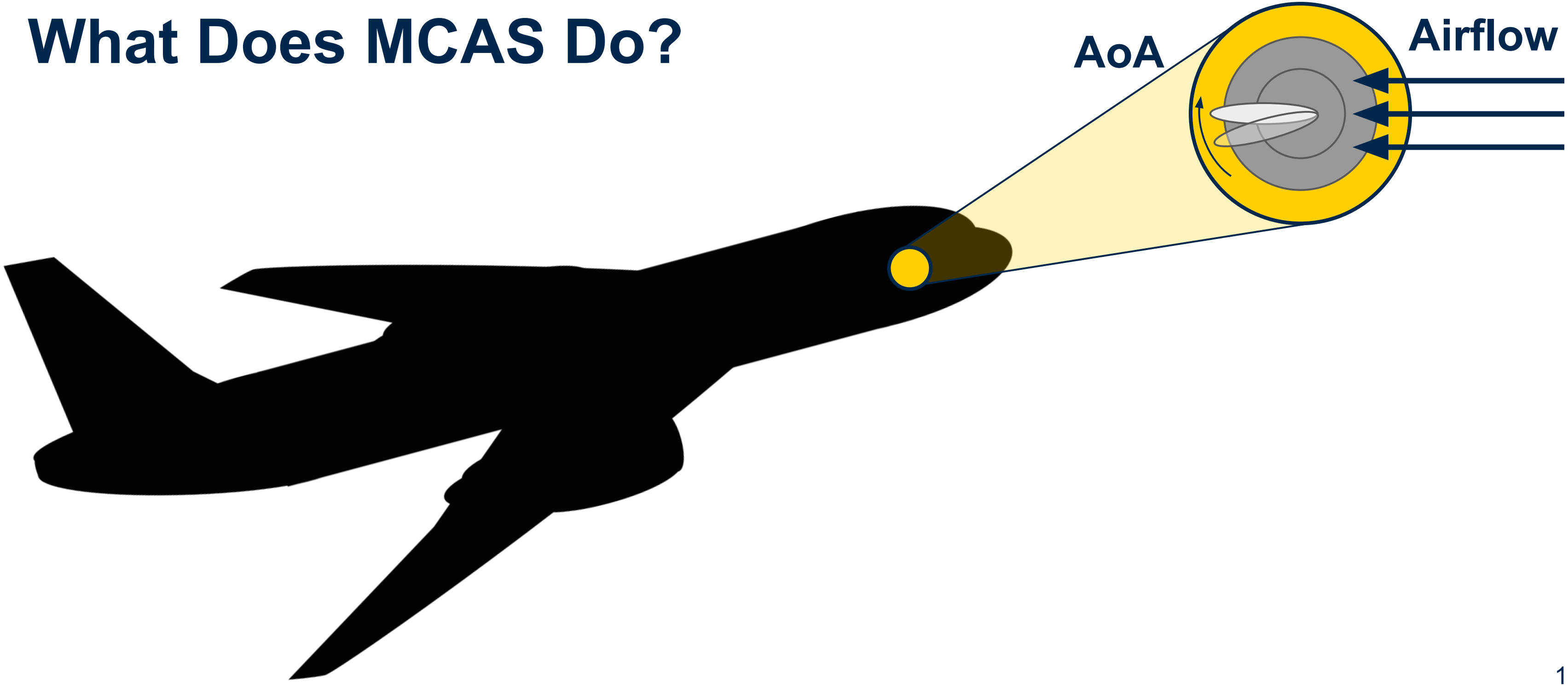

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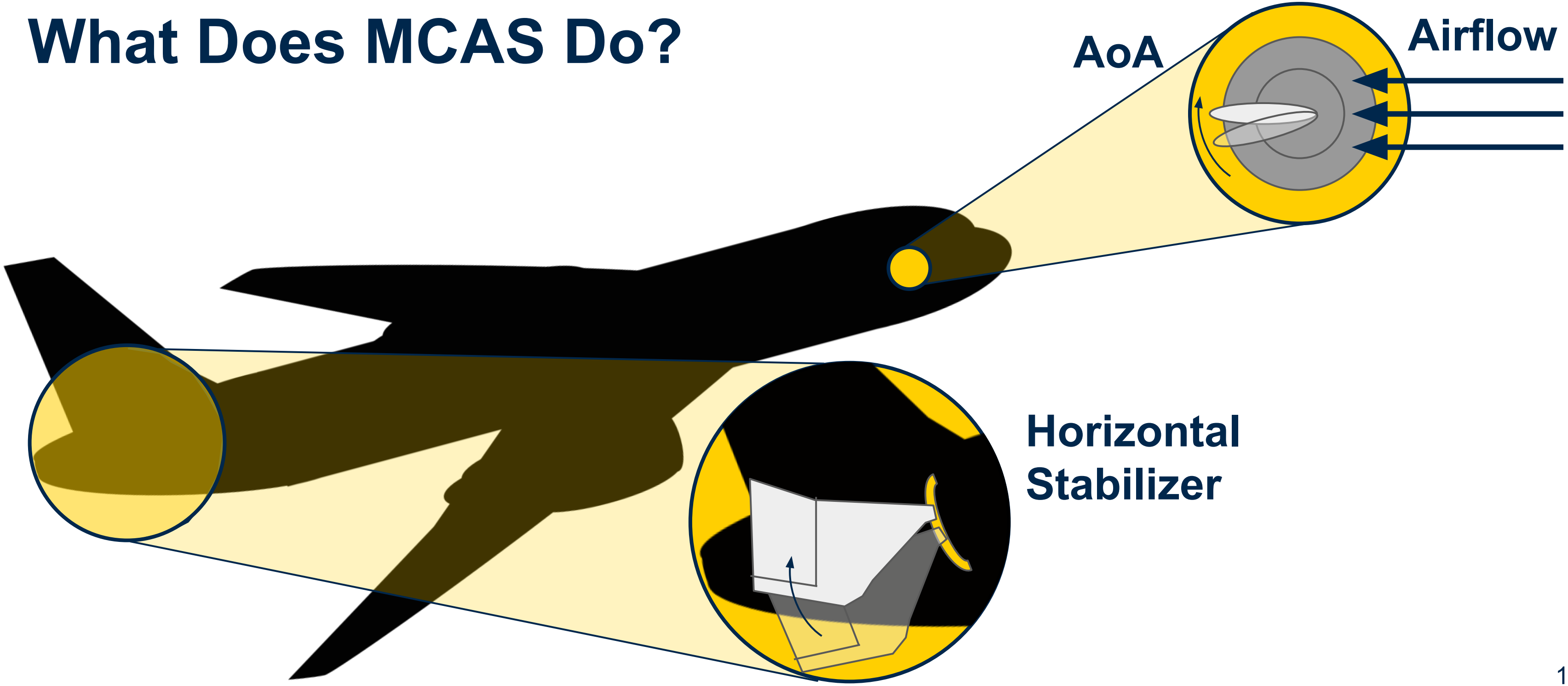

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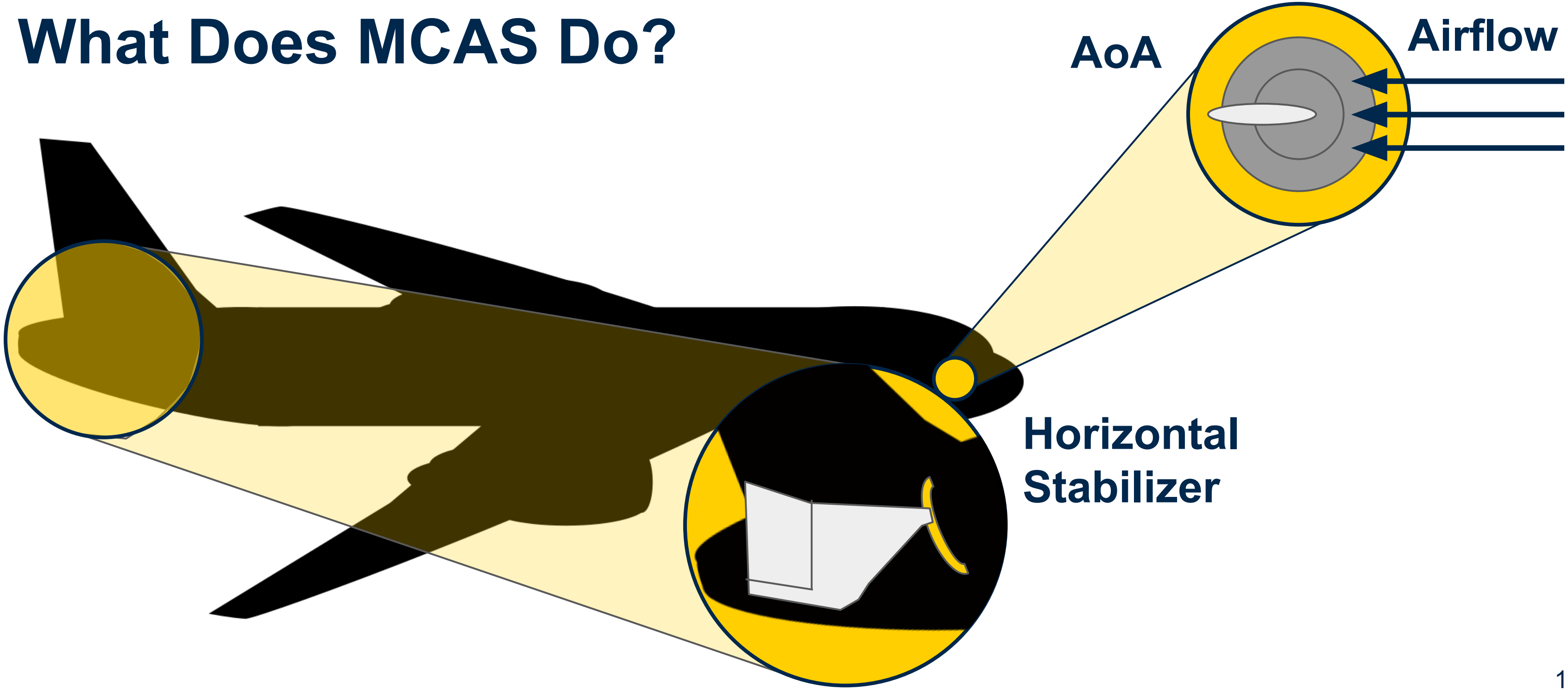
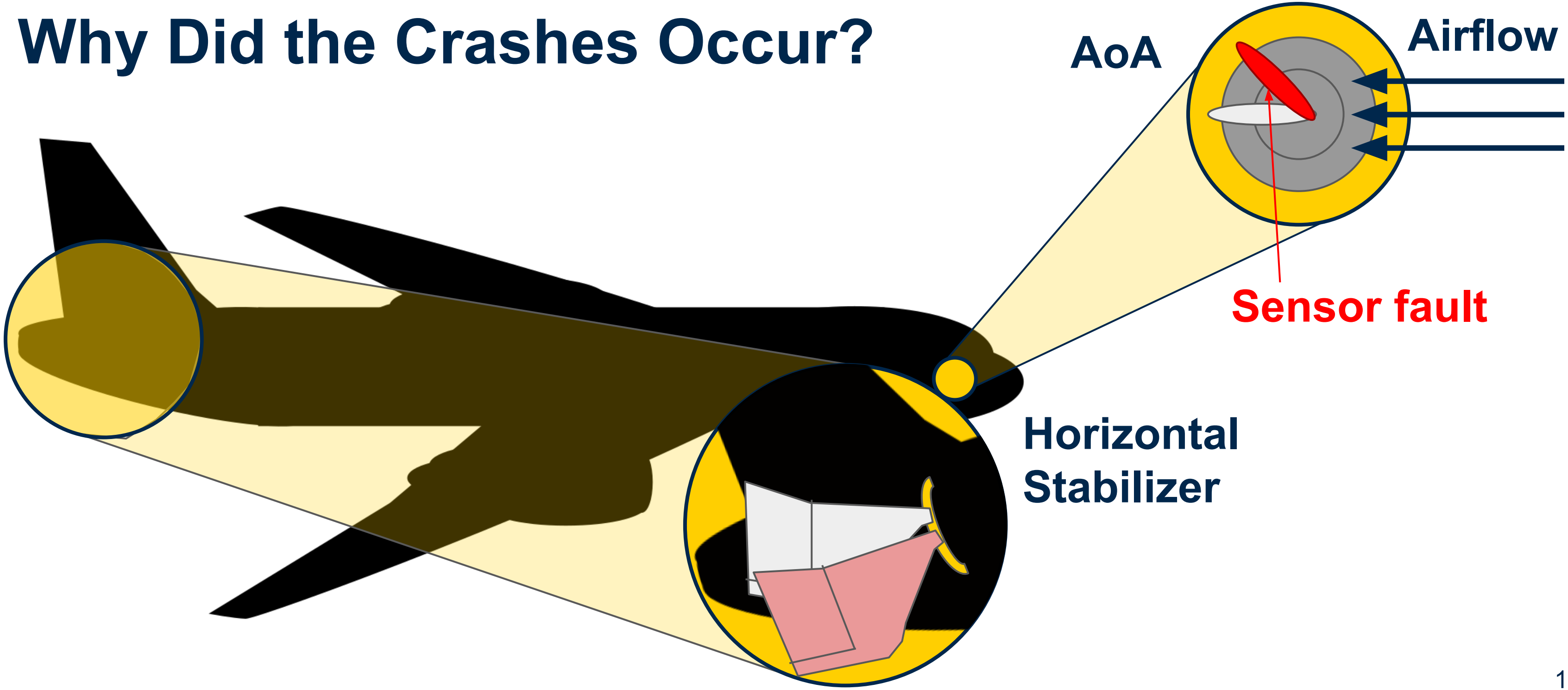


Why Did the Crashes Occur?



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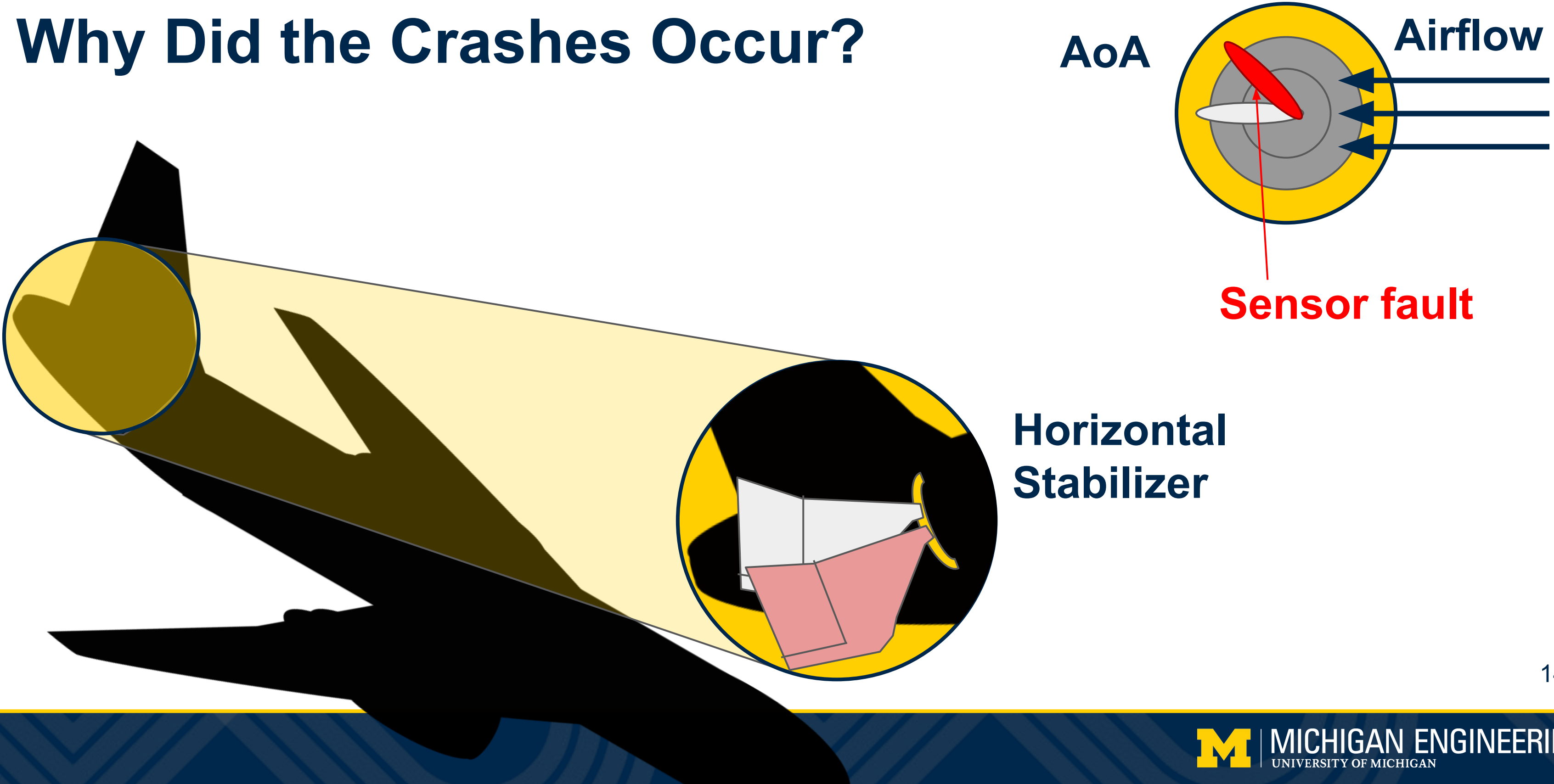
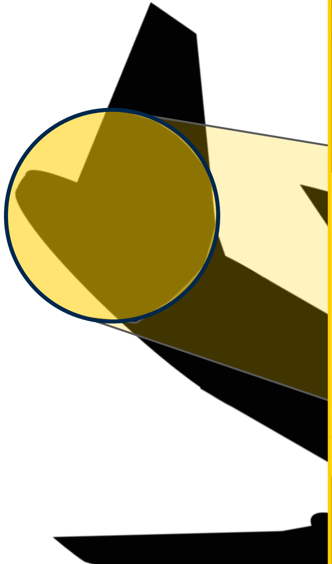
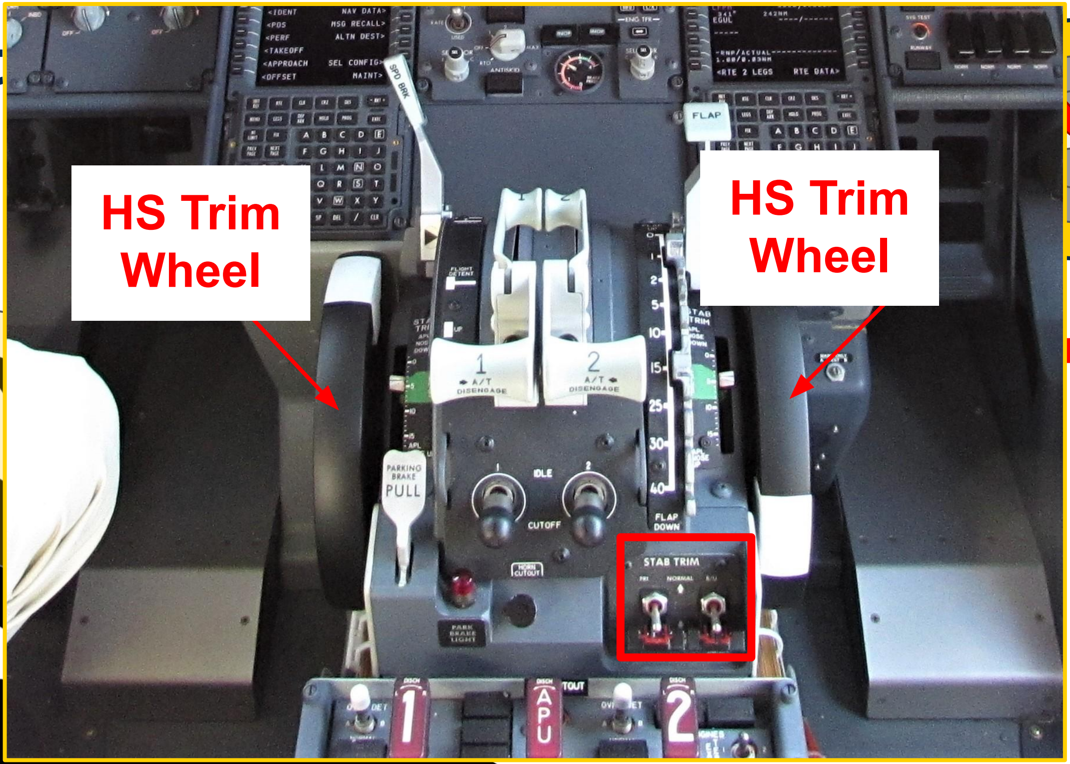


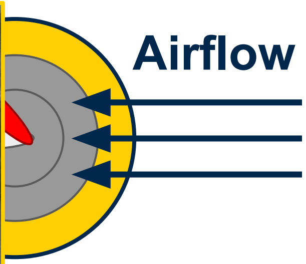
Why Did t





HS Trim Wheel

HS Trim Wheel



nsor fault

New MCAS Requirements

1. Check if all available AoA sensors exceed 17°
   - ↪ They also cannot disagree more than 5.5°

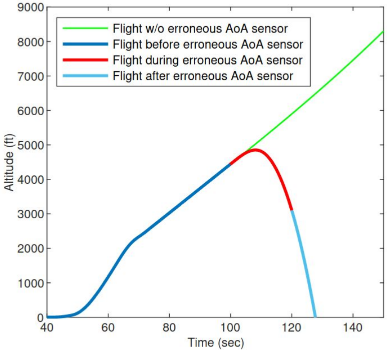
2. Using Mid-Value Select (MVS), activate MCAS only once until MVS “resets”
   - ↪ Meant to prevent runaway stabilizer problem

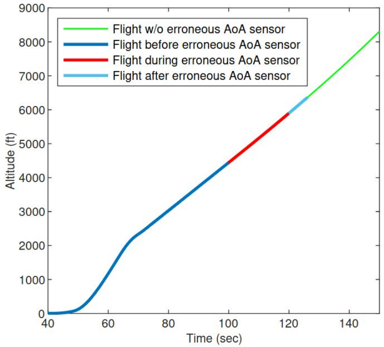
3. Pilots can manually disengage MCAS
   - ↪ Possible before, but now pilots trained to switch off *electric stabilizer trim*

Analysis of Old/New MCAS Requirements

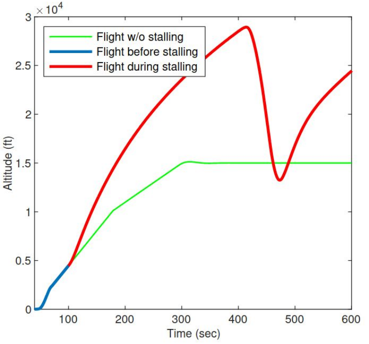
$MCAS_{old}$ ***$MCAS_{new}$***

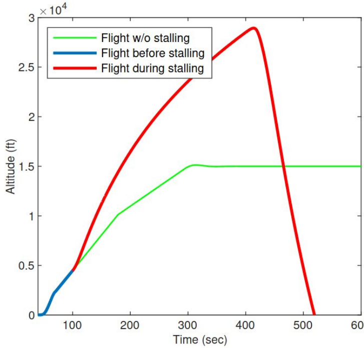
AoA Fault





Pilot Stall

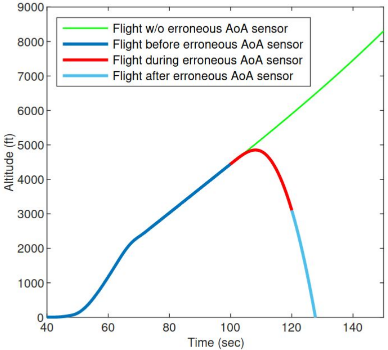


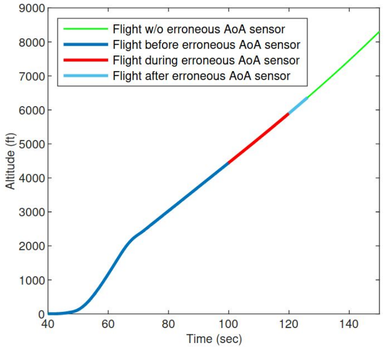


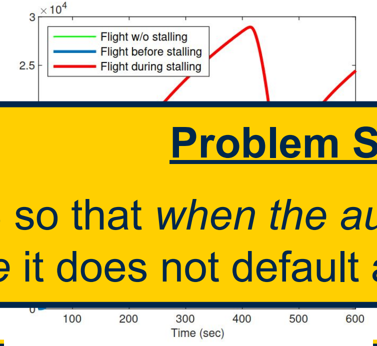
Analysis of Old/New MCAS Requirements

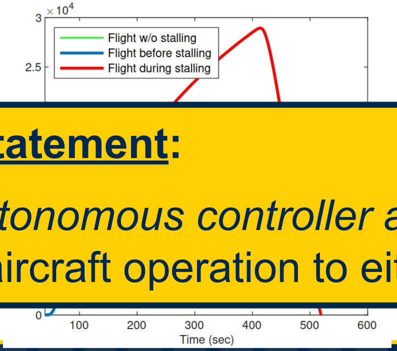
$MCAS_{old}$ **$MCAS_{new}$**

AoA Fault





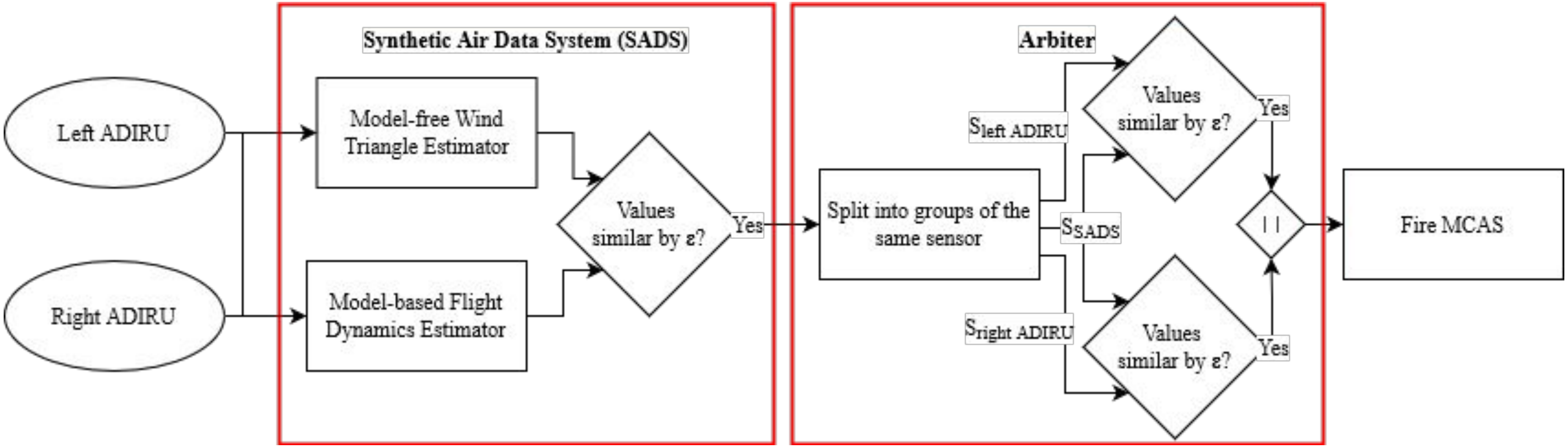




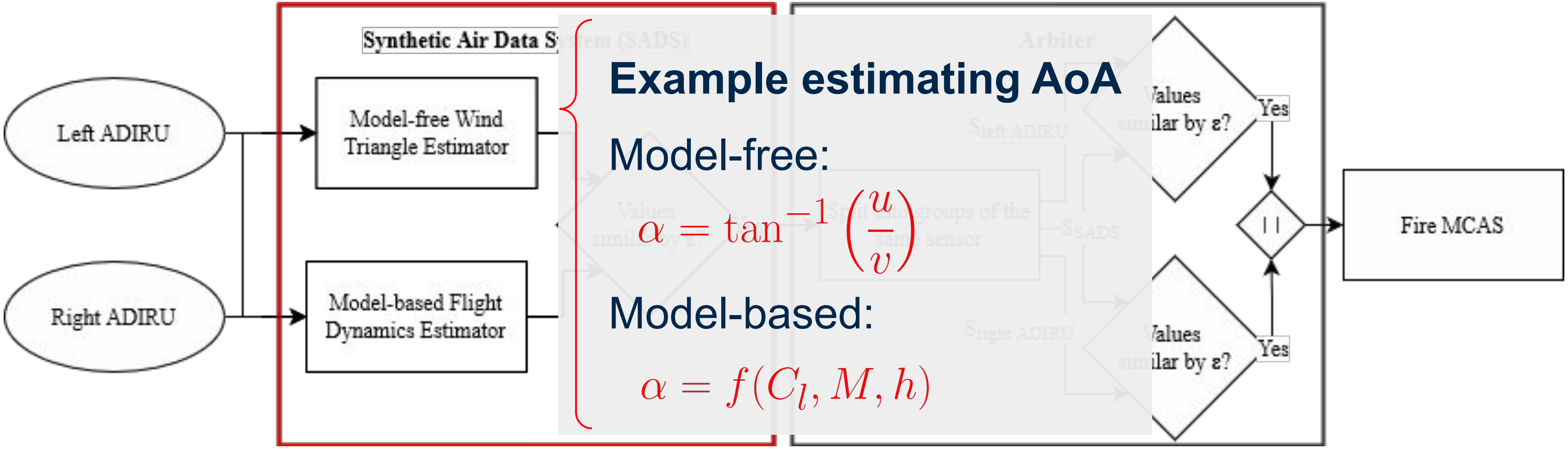
Problem Statement:

Can we design MCAS so that *when the autonomous controller and the manual pilot input disagree* it does not default aircraft operation to either agent?

Semi-Autonomous MCAS (SA-MCAS)



Synthetic Air Data System (SADS)



Example estimating AoA

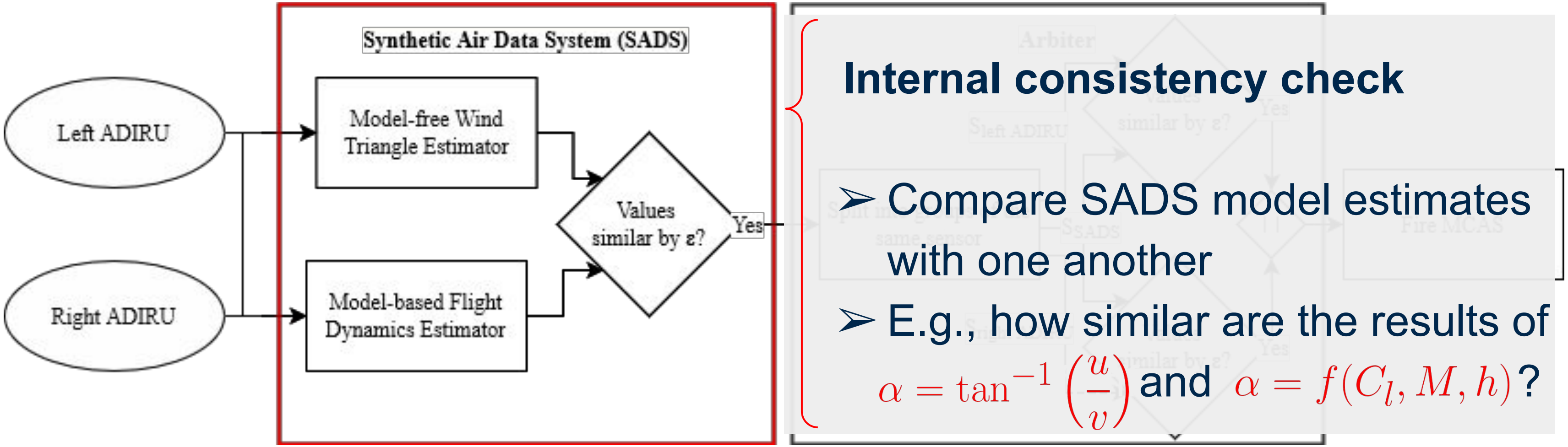
Model-free:

$$\alpha = \tan^{-1}\left(\frac{u}{v}\right)$$

Model-based:

$$\alpha = f(C_l, M, h)$$

Synthetic Air Data System (SADS)



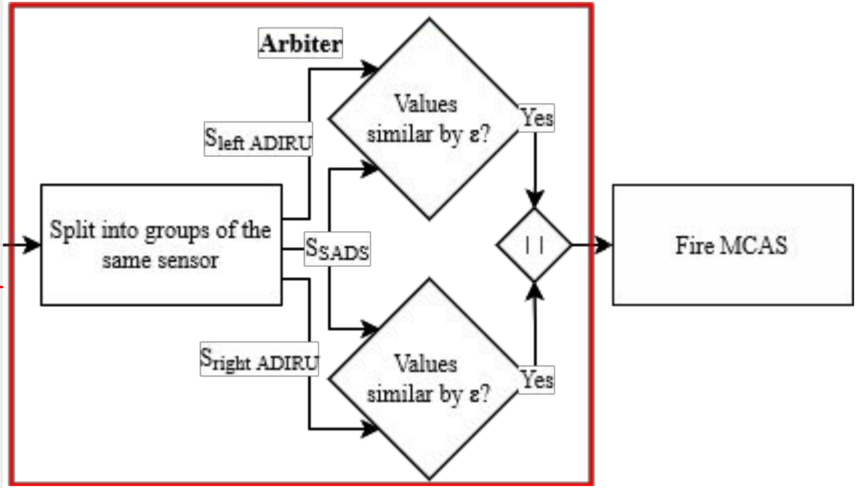
Internal consistency check

- ➢ Compare SADS model estimates with one another
- ➢ E.g., how similar are the results of $\alpha = \tan^{-1}\left(\frac{u}{v}\right)$ and $\alpha = f(C_l, M, h)$?

SA-MCAS Arbiter

External consistency check

- ➢ Compare left and right ADIRU sensor outputs with one another
- ➢ E.g., how similar are α_l and α_r to the results of the SADS model?



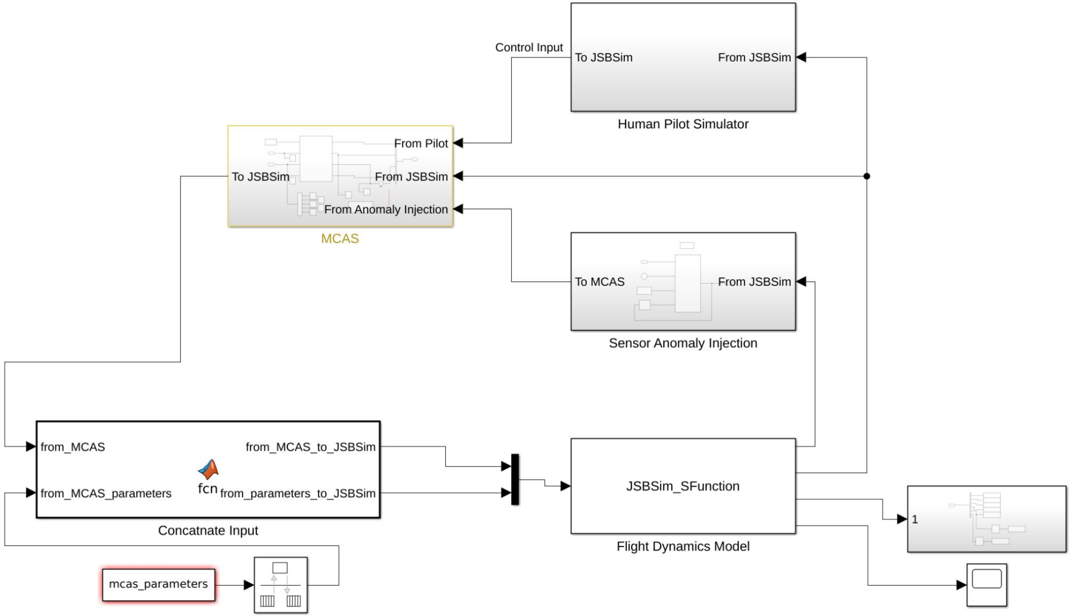
Research Challenges

➊ How to streamline the design and evaluation of MCAS without a physical aircraft?

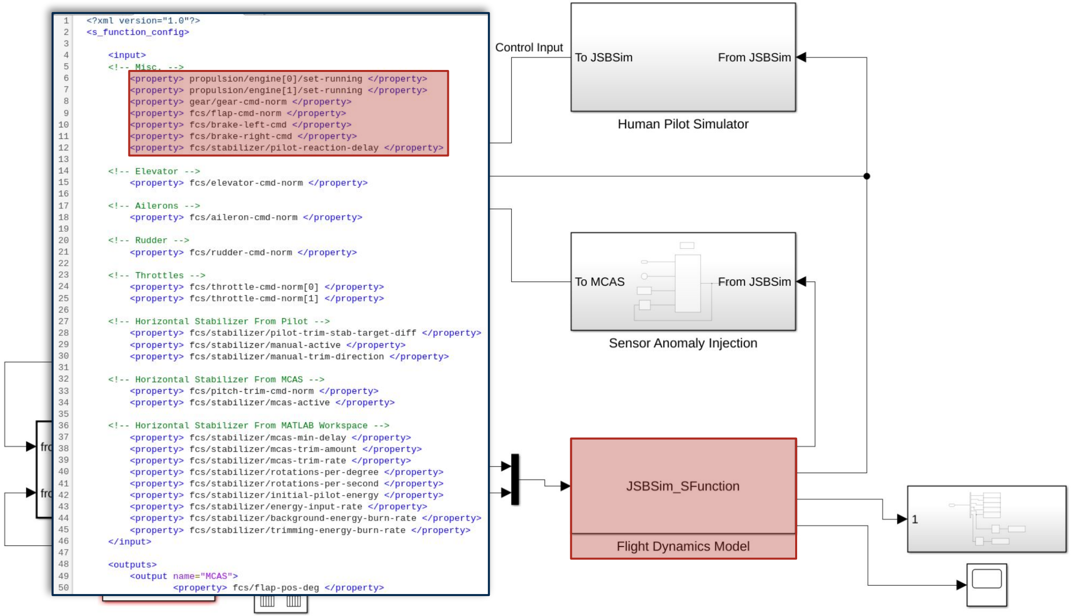
➋ Which control from MCAS and the human pilot threaten the safety of the aircraft?

➌ Does SA-MCAS mitigate the issues present in $MCAS_{old}$ and $MCAS_{new}$?

❶ Simulation of MCAS: Overview of Simulator

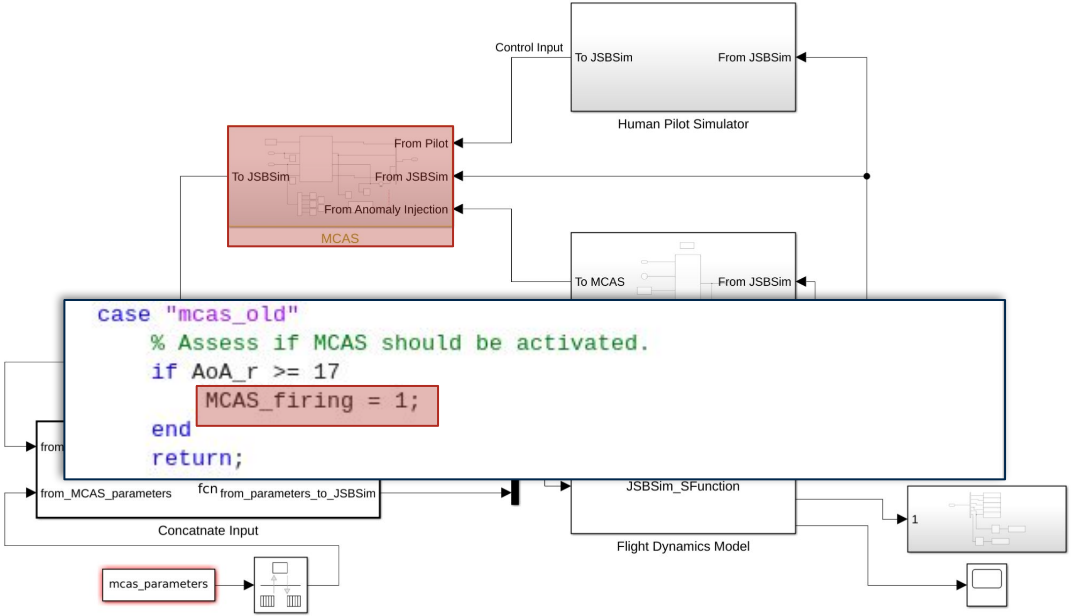


❶ Simulation of MCAS: Configuring Sensors



```xml
<?xml version="1.0"?>
<s_function_config>

    <input>
    <!-- Misc. -->
        <property> propulsion/engine[0]/set-running </property>
        <property> propulsion/engine[1]/set-running </property>
        <property> gear/gear-cmd-norm </property>
        <property> fcs/flap-cmd-norm </property>
        <property> fcs/brake-left-cmd </property>
        <property> fcs/brake-right-cmd </property>
        <property> fcs/stabilizer/pilot-reaction-delay </property>

    <!-- Elevator -->
        <property> fcs/elevator-cmd-norm </property>

    <!-- Ailerons -->
        <property> fcs/aileron-cmd-norm </property>

    <!-- Rudder -->
        <property> fcs/rudder-cmd-norm </property>

    <!-- Throttles -->
        <property> fcs/throttle-cmd-norm[0] </property>
        <property> fcs/throttle-cmd-norm[1] </property>

    <!-- Horizontal Stabilizer From Pilot -->
        <property> fcs/stabilizer/pilot-trim-stab-target-diff </property>
        <property> fcs/stabilizer/manual-active </property>
        <property> fcs/stabilizer/manual-trim-direction </property>

    <!-- Horizontal Stabilizer From MCAS -->
        <property> fcs/pitch-trim-cmd-norm </property>
        <property> fcs/stabilizer/mcas-active </property>

    <!-- Horizontal Stabilizer From MATLAB Workspace -->
        <property> fcs/stabilizer/mcas-min-delay </property>
        <property> fcs/stabilizer/mcas-trim-amount </property>
        <property> fcs/stabilizer/mcas-trim-rate </property>
        <property> fcs/stabilizer/rotations-per-degree </property>
        <property> fcs/stabilizer/rotations-per-second </property>
        <property> fcs/stabilizer/initial-pilot-energy </property>
        <property> fcs/stabilizer/energy-input-rate </property>
        <property> fcs/stabilizer/background-energy-burn-rate </property>
        <property> fcs/stabilizer/trimming-energy-burn-rate </property>
    </input>

    <outputs>
        <output name="MCAS">
            <property> fcs/flap-pos-deg </property>
```

❶ Simulation of MCAS: Building MCAS Module



```
case "mcas_old"
    % Assess if MCAS should be activated.
    if AoA_r >= 17
        MCAS_firing = 1;
    end
    return;
```

❶ Simulation of MCAS: Model Sensor Failures

Definition of sensor errors:

1. Sudden error
   - ➢ $\bar{\mathbf{x}}_s(t) = \delta$
2. Delta error
   - ➢ $\bar{\mathbf{x}}_s(t) = \mathbf{x}_s(t) + \delta$
3. Gradual error
   - ➢ $\bar{\mathbf{x}}_s(t) = \mathbf{x}_s(t_0) + f(t)$

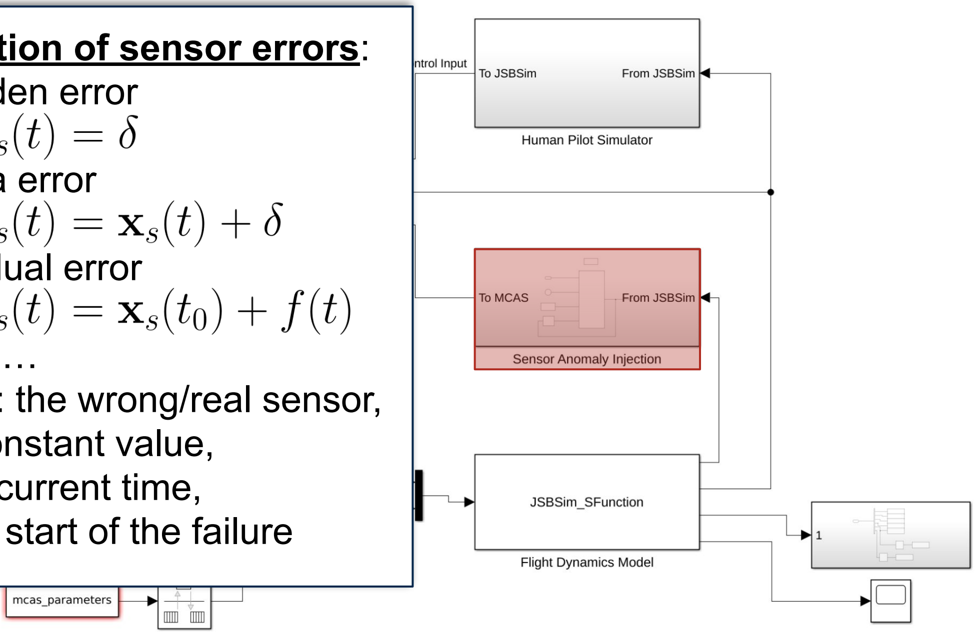
Where…

$\bar{\mathbf{x}}_s$ / $\mathbf{x}_s$: the wrong/real sensor,

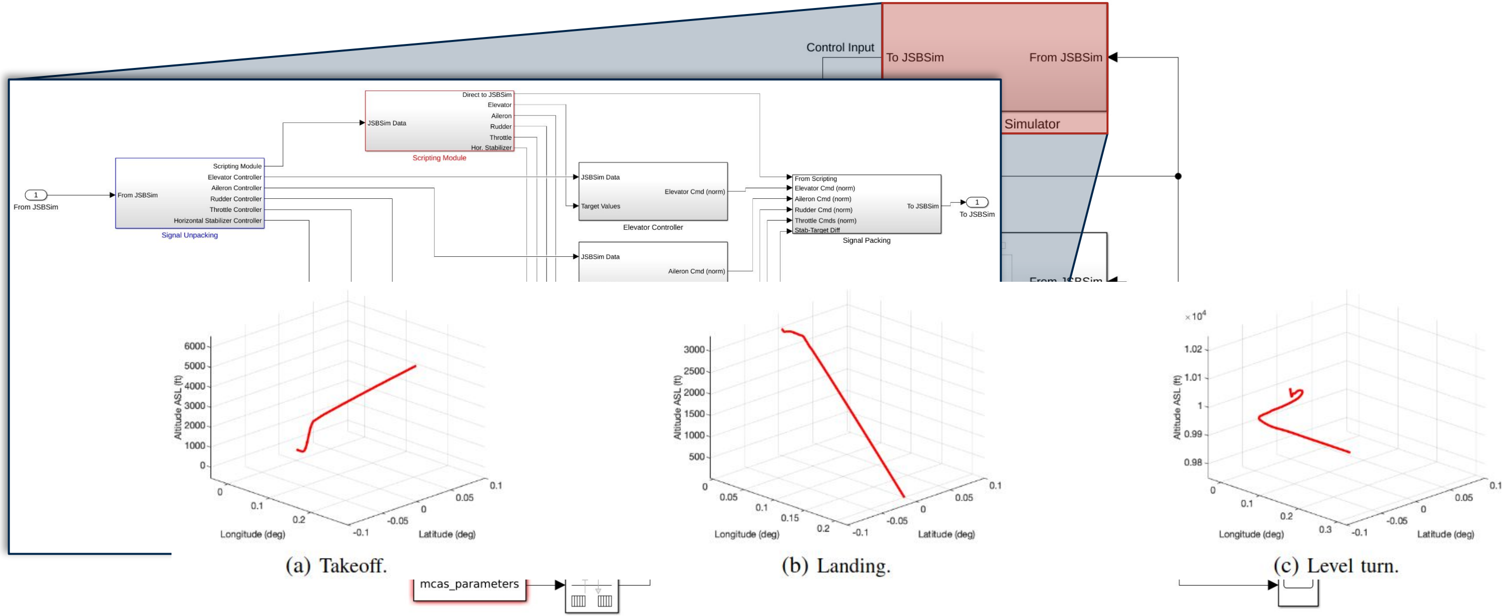
δ: a constant value,

t: the current time,

t_0: the start of the failure



❶ Simulation of MCAS: Model Pilot Control



(a) Takeoff.

(b) Landing.

(c) Level turn.

Research Challenges

❶ **How to streamline the design and evaluation of MCAS without a physical aircraft?**

- We provide an open-source toolkit built on JSBSim.
- We validate the correctness and usefulness of the simulations and include guidelines for using this toolkit.

❷ **Which control from MCAS and the human pilot threaten the safety of the aircraft?**

❸ **Does SA-MCAS mitigate the issues present in $MCAS_{old}$ and $MCAS_{new}$?**

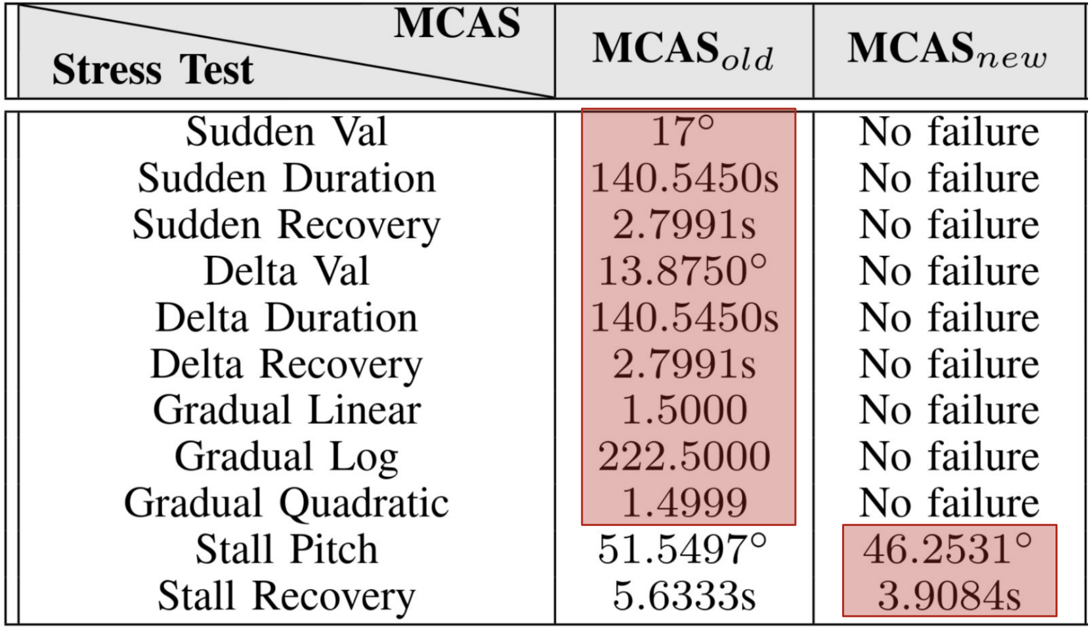
❷ Experiment Setup (Sensor Fault)

- Sudden and delta errors:
  1. $\boxed{\delta \in [0, 90]^\circ}$ $t \in [100, 150]s$ pilot react after 5s
  2. $\delta = 18^\circ$ $\boxed{t \in [100, t_{end}]s \quad t_{end} \in [110, 180]s}$ pilot react after 5s
  3. $\delta = 18^\circ$ $t \in [100, 150]s$ $\boxed{\text{pilot react after} \in [0, 10]s}$
- Gradual errors:
  - ○ $f(t) = at,$ $\boxed{a \in [0, 3]}$ $f(t) = a\log(t),$ $\boxed{a \in [0, 500]}$ $f(t) = at^2,$ $\boxed{a \in [0, 3]}$
  - ○ Pilot react after 5s
- If MCAS activates, pilot trims horizontal stabilizer at rate of 3.5 RPS

❷ Experiment Setup (Pilot Fault)

1. Pitch variation
    - Pilot pitches aircraft $\in \boxed{[20, 90]^\circ}$
    - If MCAS activates, pilot responds in 5s
2. Response variation
    - Pilot pitches aircraft 50°
    - If MCAS activates, pilot responds in $\in \boxed{[0, 10]s}$

❷ Analysis of MCAS$_{old}$ and MCAS$_{new}$ Summary



MCAS Stress Test	MCAS$_{old}$	MCAS$_{new}$
Sudden Val	17°	No failure
Sudden Duration	140.5450s	No failure
Sudden Recovery	2.7991s	No failure
Delta Val	13.8750°	No failure
Delta Duration	140.5450s	No failure
Delta Recovery	2.7991s	No failure
Gradual Linear	1.5000	No failure
Gradual Log	222.5000	No failure
Gradual Quadratic	1.4999	No failure
Stall Pitch	51.5497°	46.2531°
Stall Recovery	5.6333s	3.9084s

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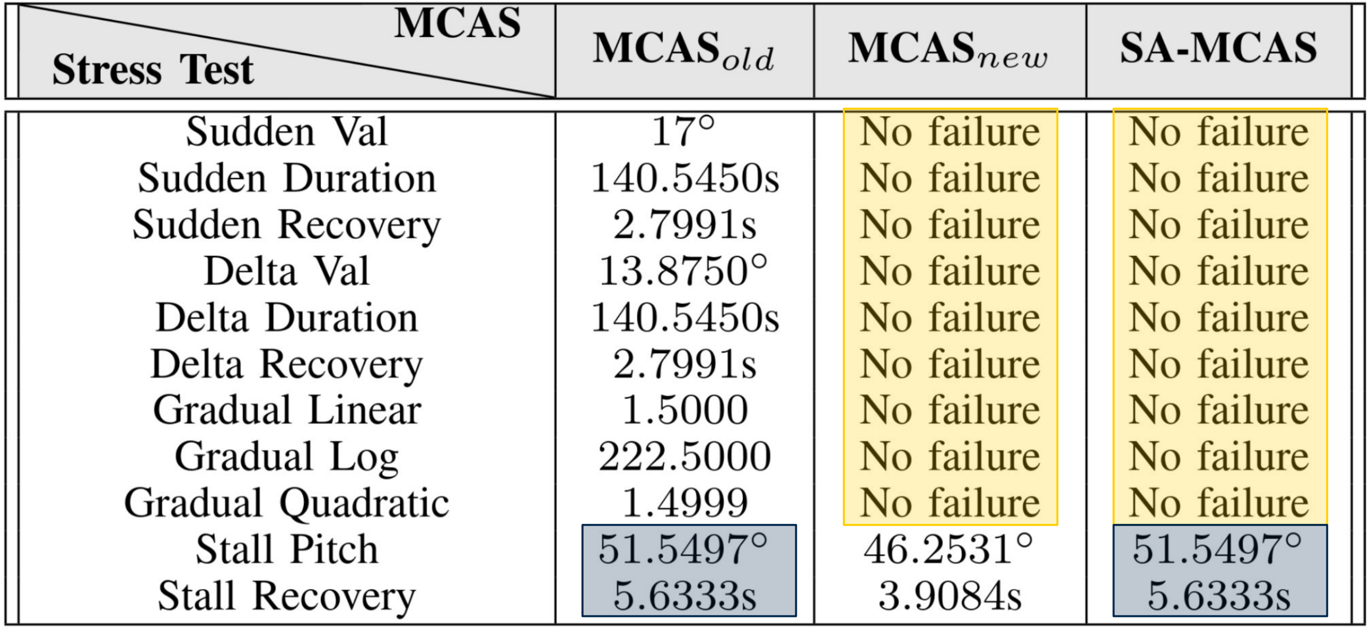
❷ **Which control from MCAS and the human pilot threaten the safety of the aircraft?**

- We demonstrate threats that show the new Boeing MCAS design is susceptible to dangerous control from the pilot.
- Our analysis unveils precise upper bounds for aircraft recoverability during erroneous MCAS events.

❸ **Does SA-MCAS mitigate the issues present in $MCAS_{old}$ and $MCAS_{new}$?**

❸ Analysis of SA-MCAS



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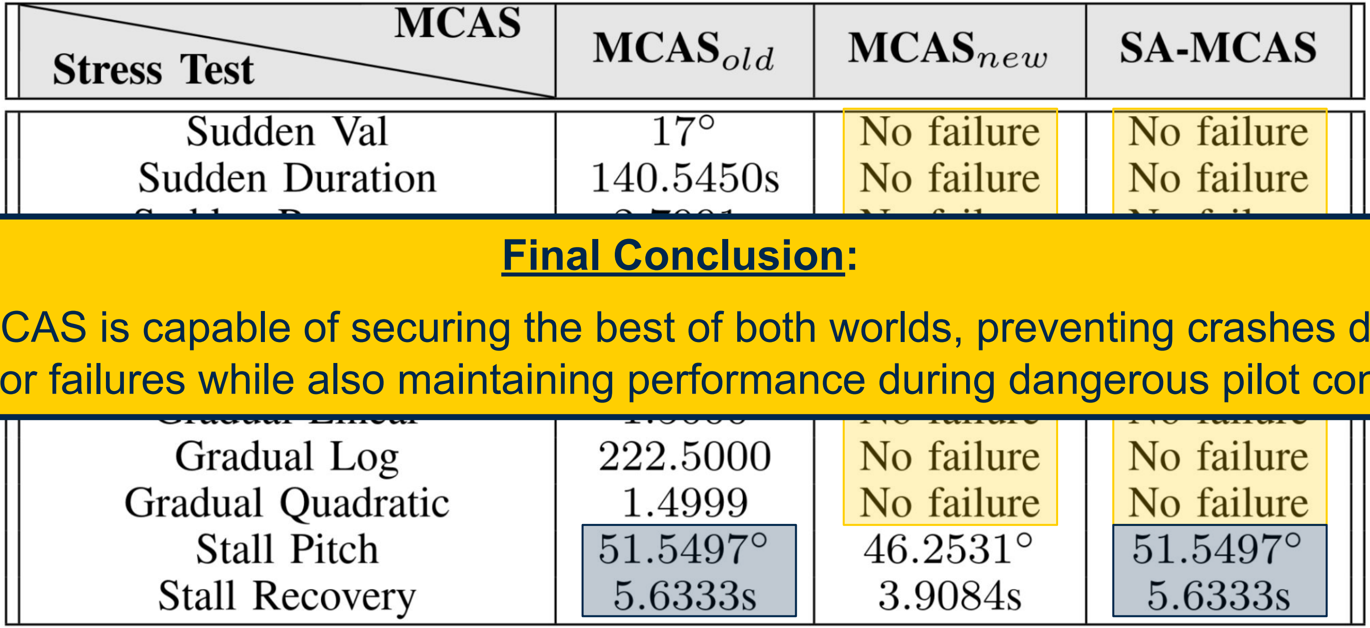
❸ Evaluation of SA-MCAS



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Stall Pitch	51.5497°	46.2531°	51.5497°
Stall Recovery	5.6333s	3.9084s	5.6333s

Final Conclusion:

SA-MCAS is capable of securing the best of both worlds, preventing crashes during sensor failures while also maintaining performance during dangerous pilot control.

Research Challenges

❶	**How to streamline the design and evaluation of MCAS without a physical aircraft?**	● We provide an open-source toolkit built on JSBSim flight. ● We validate the correctness and usefulness of the simulations and include guidelines for using this toolkit.
❷	**Which control from MCAS and the human pilot threaten the safety of the aircraft?**	● We demonstrate threats that show the new Boeing MCAS design is susceptible to dangerous control from the pilot. ● Our analysis unveils precise upper bounds for aircraft recoverability during erroneous MCAS events.
❸	**Does SA-MCAS mitigate the issues present in MCAS_{old} and MCAS_{new}?**	● We evaluate SA-MCAS, which is capable of resolving conflicts between the manual and automatic control. ● It is capable of performing the best of MCAS_{old} / MCAS_{new}

Discussion and Future Work

- Discussion
    - Passenger trust still needs to be regained
    - Limited ability to prevent dangerous pilot control

- Future Work
    - What do we do when neither the pilot nor the autonomous control is safe?
    - Currently do equal to better of autonomous/manual control, but can we do better?

Questions?

Takeaways:

- Semi-autonomous systems should not default control to manual operator or autonomous controller
- SA-MCAS provides dynamic control arbitration for 737-MAX

Contributors

Funding

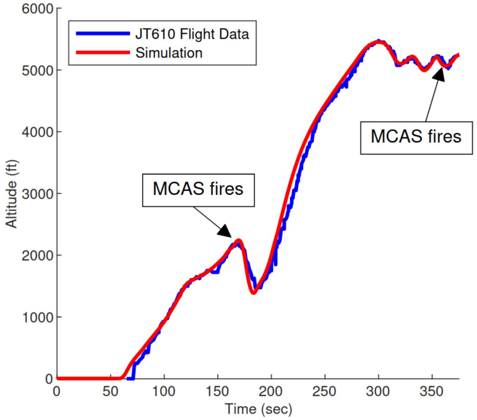
Office of Naval Research
ONR
Science & Technology

Paper URL

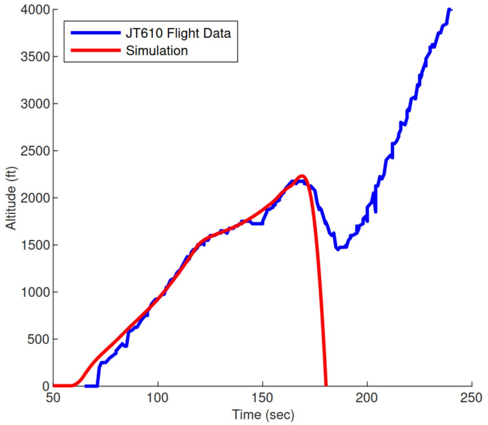
❶ Simulation of MCAS: Validation

JT610 Crash Simulation Using the Modeling Toolkit

Pilot Intervention



No Pilot Intervention

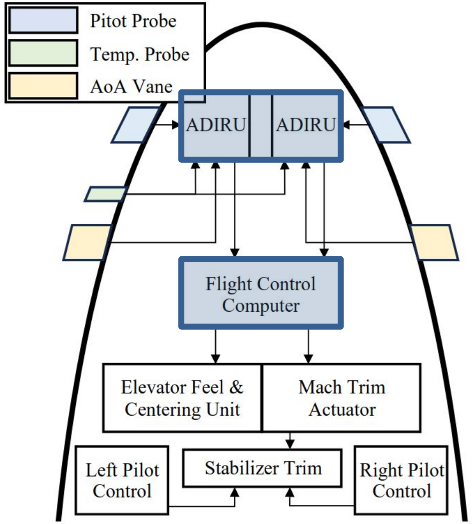


Why Did the 737-MAX Crashes Occur?

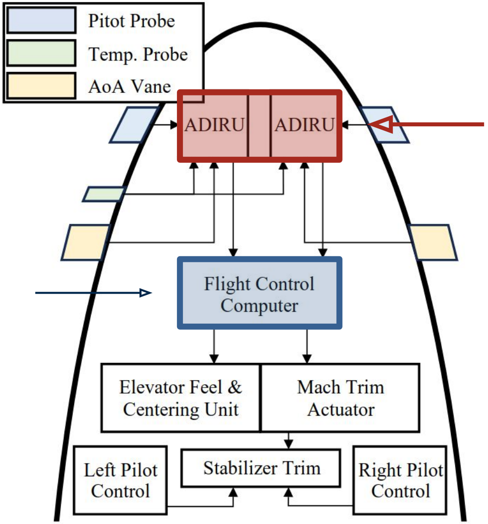
Sources: Boeing, Mentourpilot

Bloomberg

Boeing 737 Aircraft Network



Synthetic Air Data System (SADS)



SA-MCAS

SADS

Example estimating AoA

Model Free:

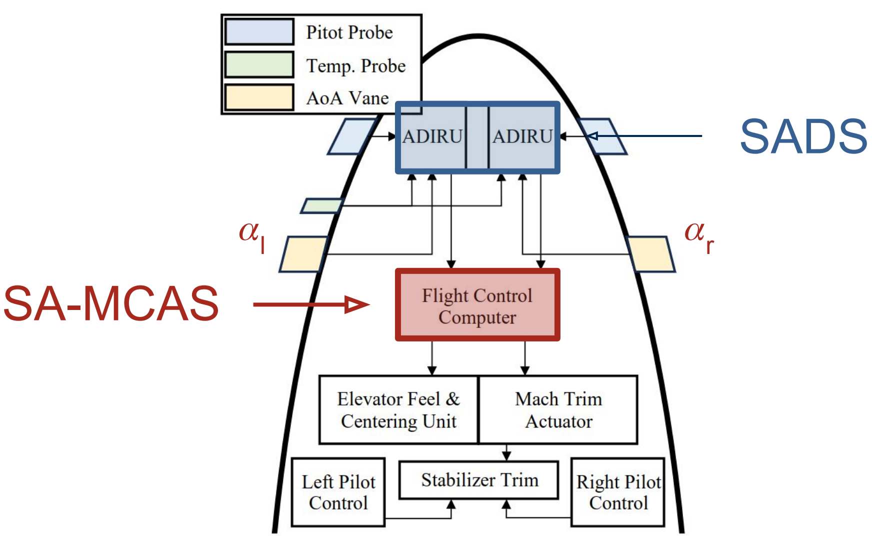
$$\alpha = \tan^{-1}\left(\frac{u}{v}\right)$$

Model Based:

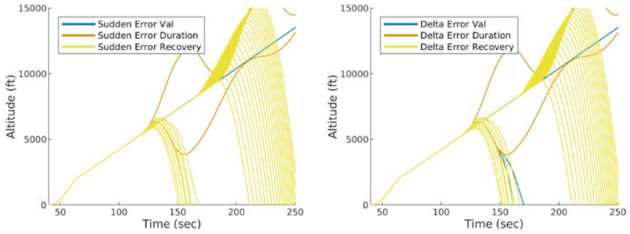
$$\alpha = f(C_l, M, h)$$

Semi-Autonomous MCAS (SA-MCAS)

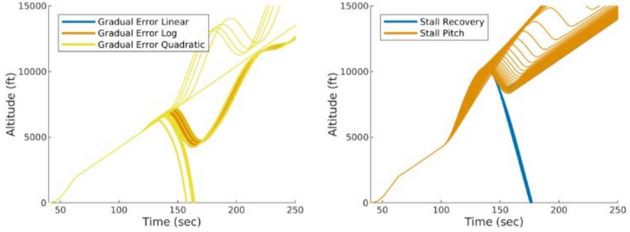
1. Internal consistency check
   - ➢ Compare SADS model estimates with one another
   - ➢ E.g., how similar are the results of $\alpha = \tan^{-1}\left(\frac{u}{v}\right)$ and $\alpha = f(C_l, M, h)$?
2. External consistency check
   - ➢ Compare left and right ADIRU sensor outputs with one another
   - ➢ E.g., how similar are α_l and α_r to the results of the SADS model?



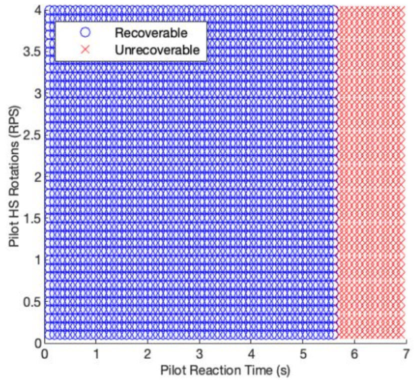
❷ How Does $MCAS_{old}$ Cause Dangerous Control?



(a) Sudden error flight paths. (b) Delta error flight paths.



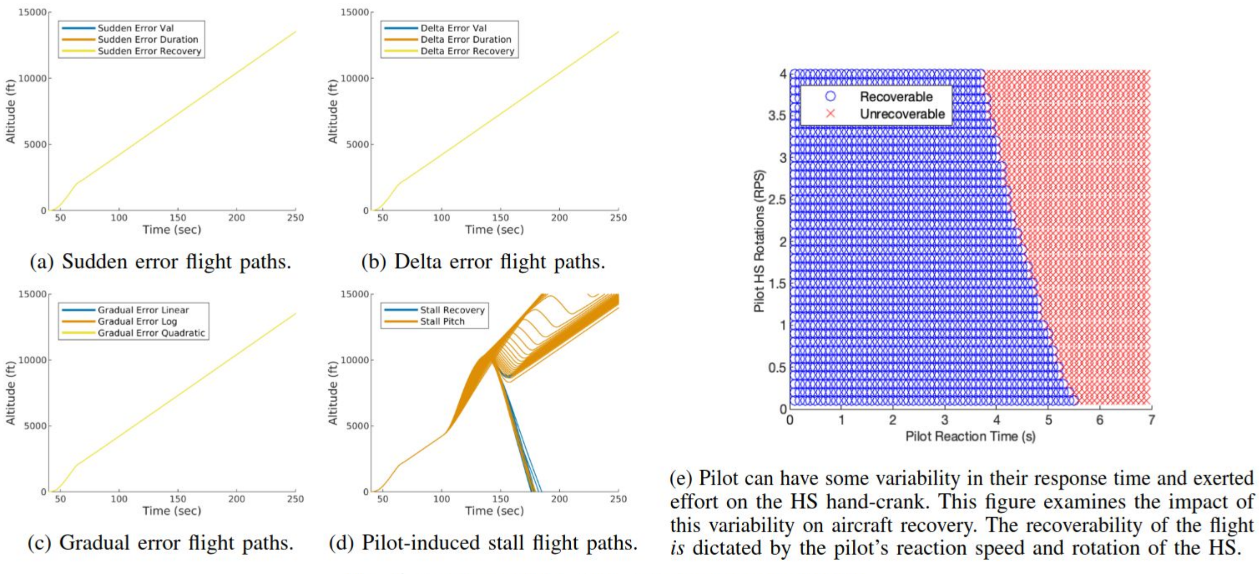
(c) Gradual error flight paths. (d) Pilot-induced stall flight paths.



(e) Pilot can have some variability in their response time and exerted effort on the HS hand-crank. This figure examines the impact of this variability on aircraft recovery. The recoverability of the flight *is not* dictated by the pilot's reaction speed and rotation of the HS.

Fig. 5: Summary of the stress test simulation for MCAS_{old}.

❷ How Does $MCAS_{new}$ Cause Dangerous Control?



(a) Sudden error flight paths.

(b) Delta error flight paths.

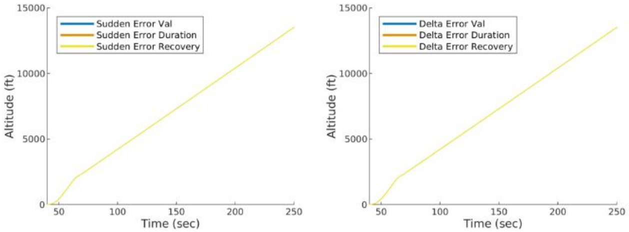
(c) Gradual error flight paths.

(d) Pilot-induced stall flight paths.

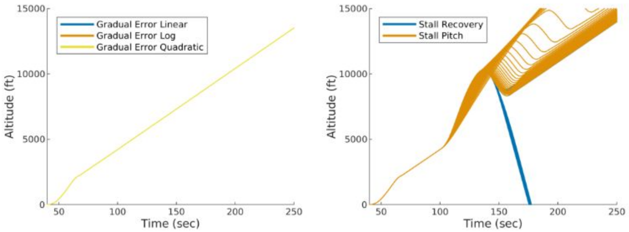
(e) Pilot can have some variability in their response time and exerted effort on the HS hand-crank. This figure examines the impact of this variability on aircraft recovery. The recoverability of the flight *is* dictated by the pilot's reaction speed and rotation of the HS.

Fig. 6: Summary of the stress test simulation for MCAS_{new}.

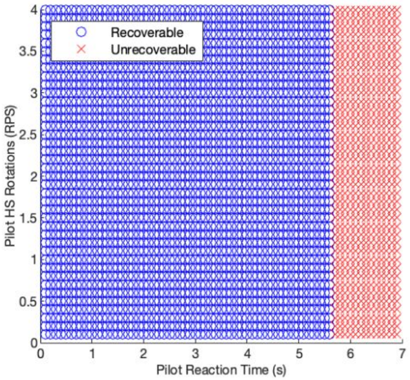
❸ Evaluation of SA-MCAS



(a) Sudden error flight paths. (b) Delta error flight paths.



(c) Gradual error flight paths. (d) Pilot-induced stall flight paths.



(e) Pilot can have some variability in their response time and exerted effort on the HS hand-crank. This figure examines the impact of this variability on aircraft recovery. The recoverability of the flight *is not* dictated by the pilot's reaction speed and rotation of the HS.

Fig. 7: Summary of the stress test simulation for SA-MCAS.