IMUFUZZER:
Resilience-based Discovery of Signal Injection Attacks on Robotic Aerial Vehicles

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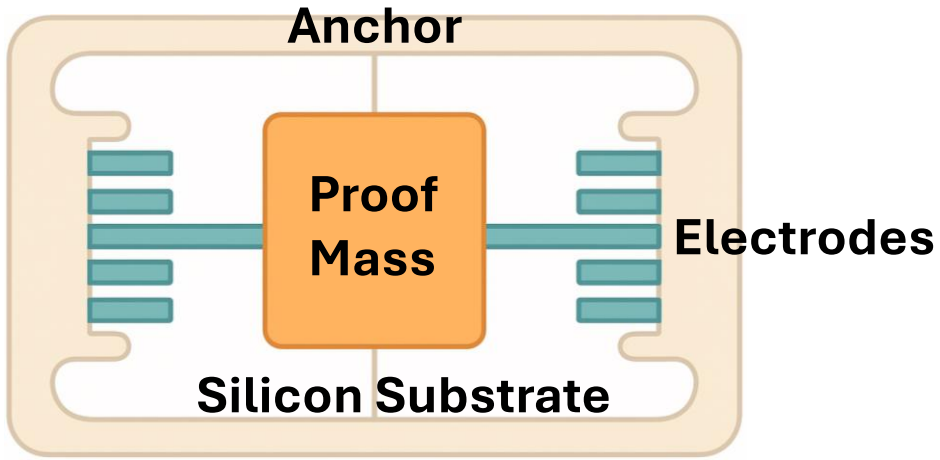
MEMS IMU Sensors

- **IMU Sensors –** Accelerometers and Gyrocopes.

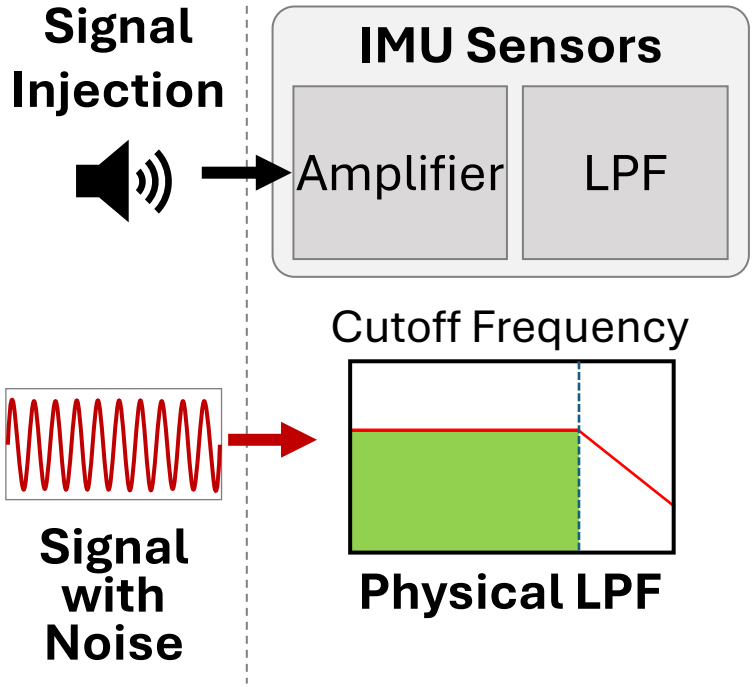
Sensor	Measures
Accelerometer	Speed/Acceleration
Gyroscope	Roll, Pitch & Yaw

- **MEMS Sensors –** Micro-electro-mechanical systems.



Signal Injection Attacks

- Sensor spoofing with acoustic signals [USENIX Sec'15, EuroS&P'17, USENIX Sec.'18].



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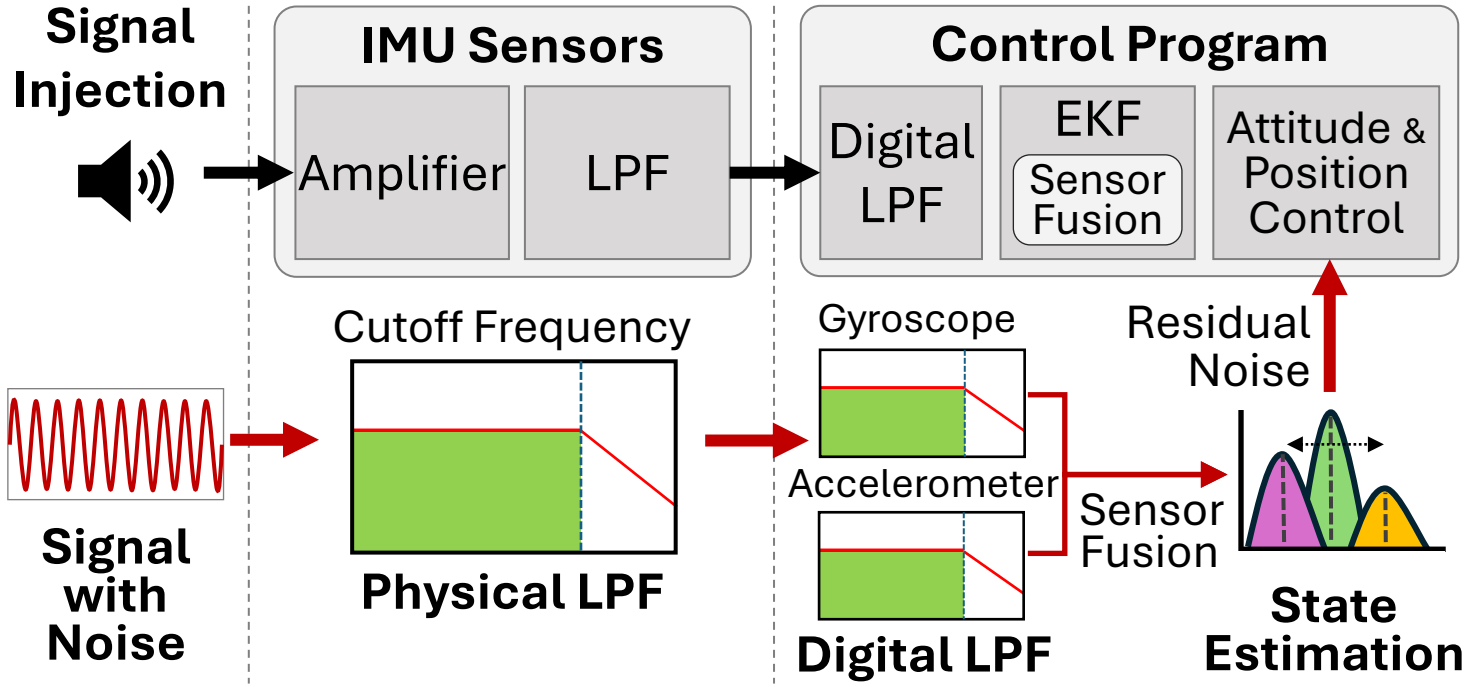

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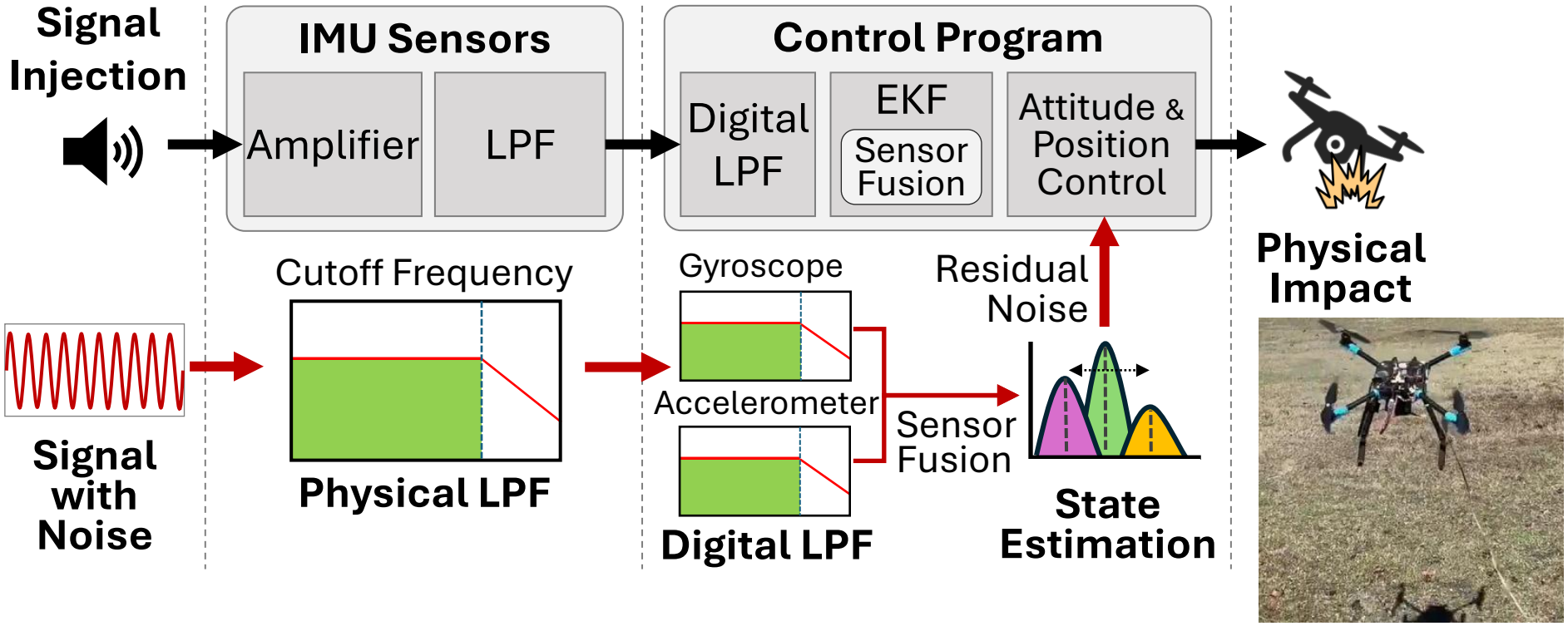

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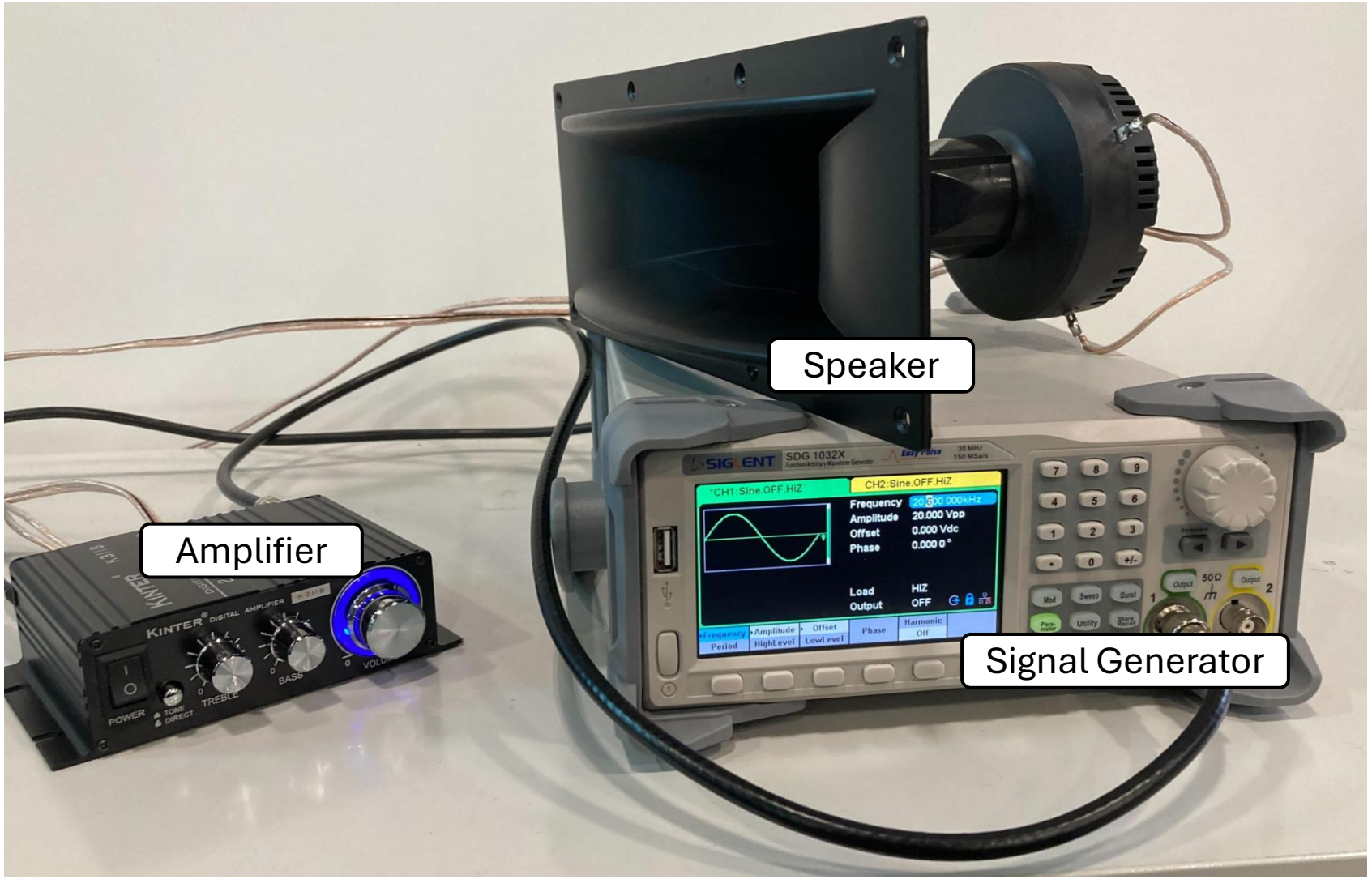

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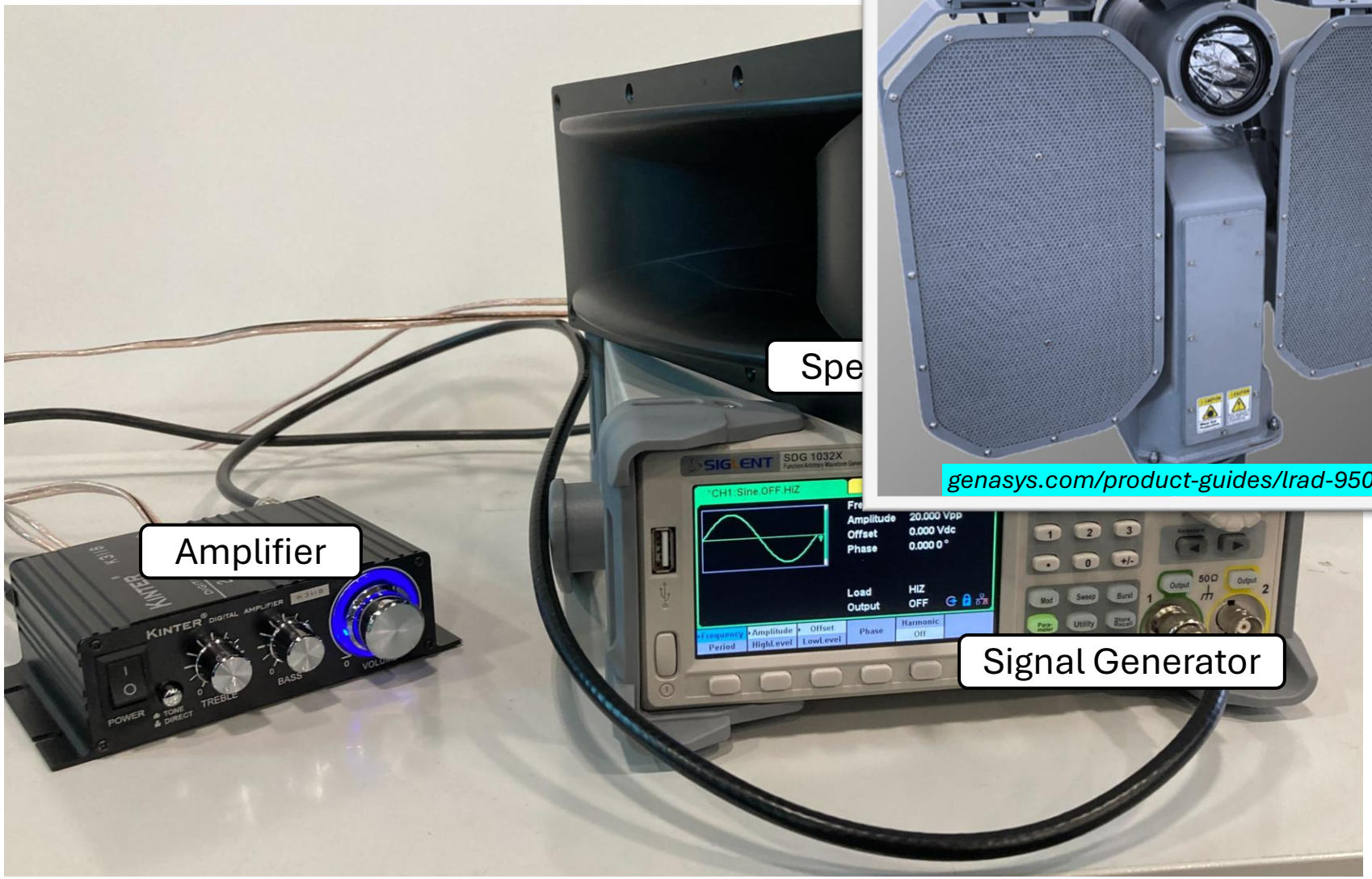

Do The Same Attacks Work In All Cases?

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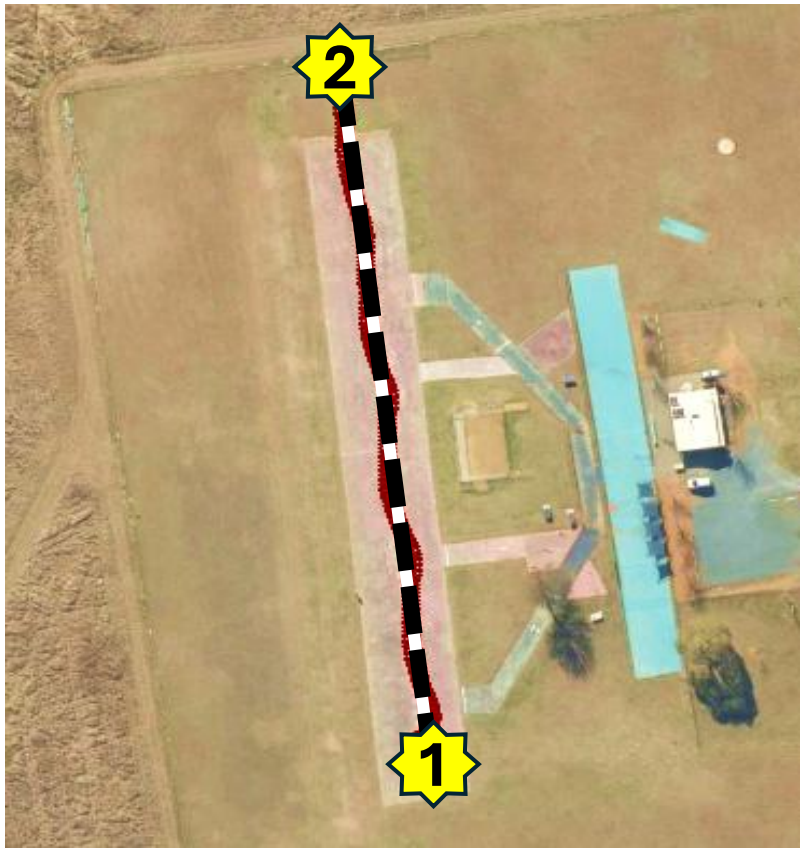
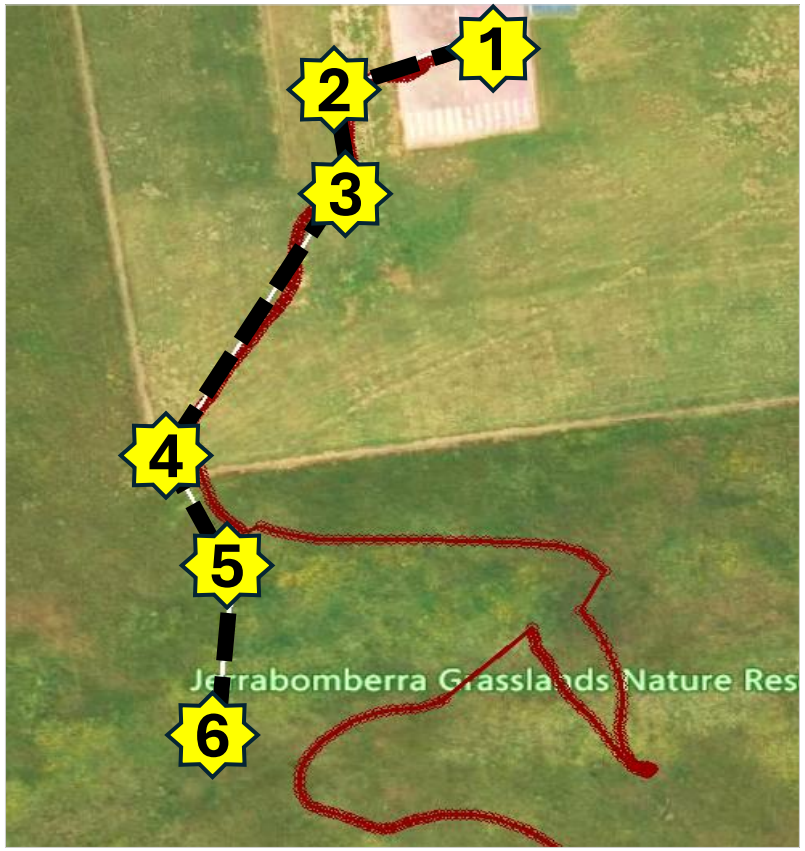
No. Same Attacks ≠ Same Impacts.





Actual Path
Mission Path
Waypoints

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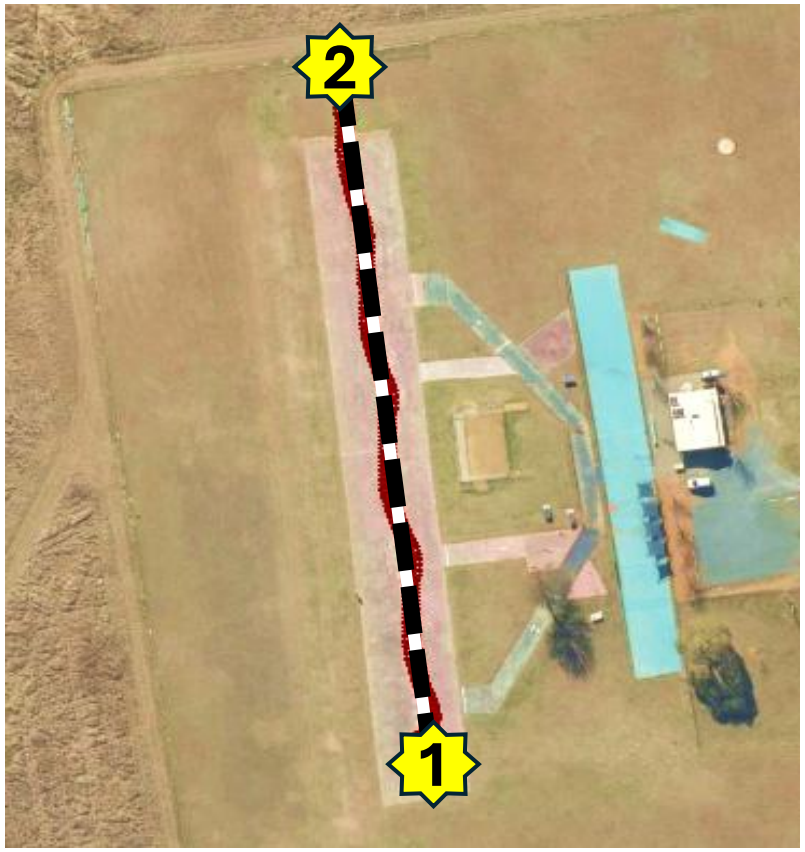

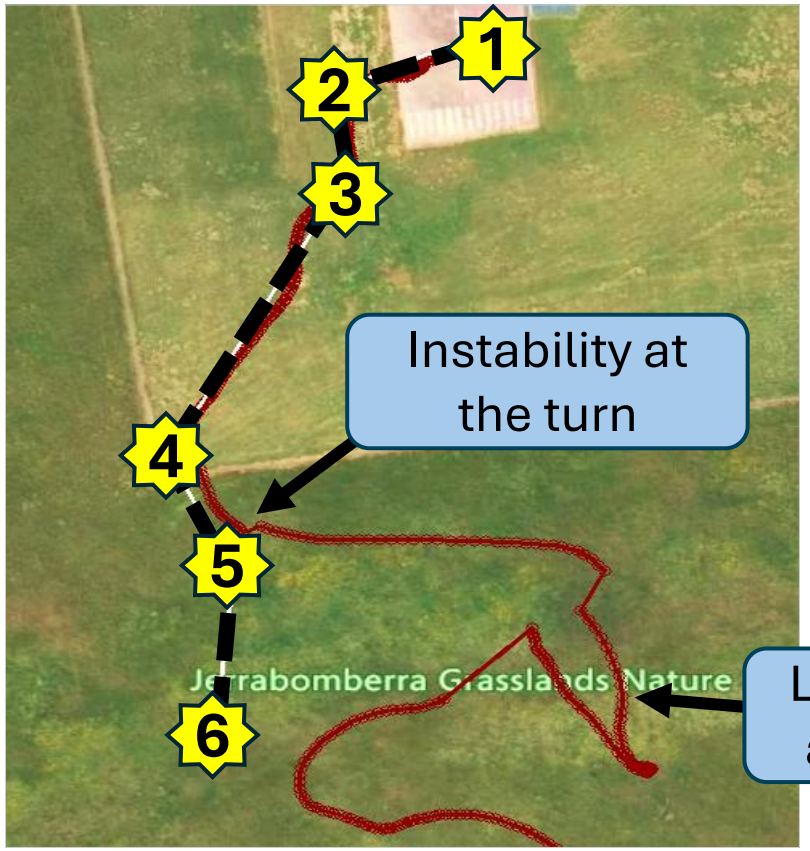

Actual Path
Mission Path
Waypoints

Change in physical states triggers crash!

IMUFUZZER's Approach

- We present ***IMUFUZZER***:

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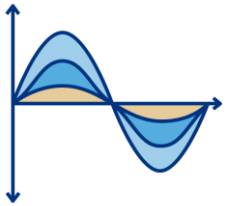

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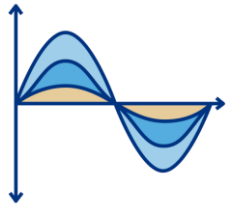
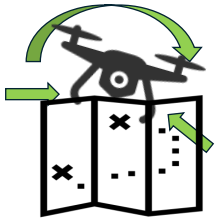


  - Explore **physical states** to find **hidden attacks**.



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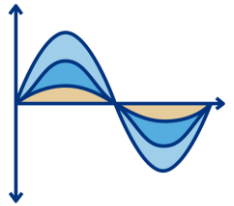

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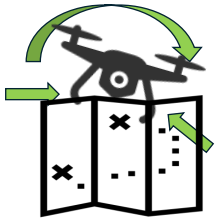

  - **Control-aware feedback** for efficient sensor fuzzing.

Inputs To Fuzzer

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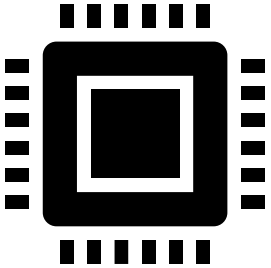

Sensor Profile

Derived from real-world
IMU sensors

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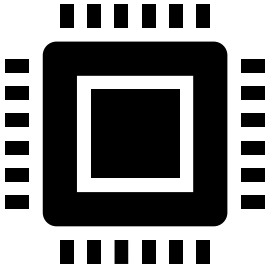

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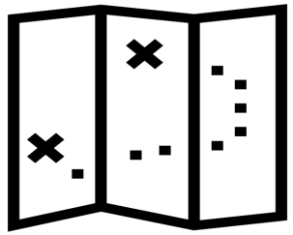

Seed Mission

1. Waypoints
2. Distances
3. Angles

Sensor Input Generator

- Injects sine waves with varying **amplitude & frequency.**

$$A * sin(2\pi Ft + \phi)$$

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- Injects sine waves with varying **amplitude & frequency.**

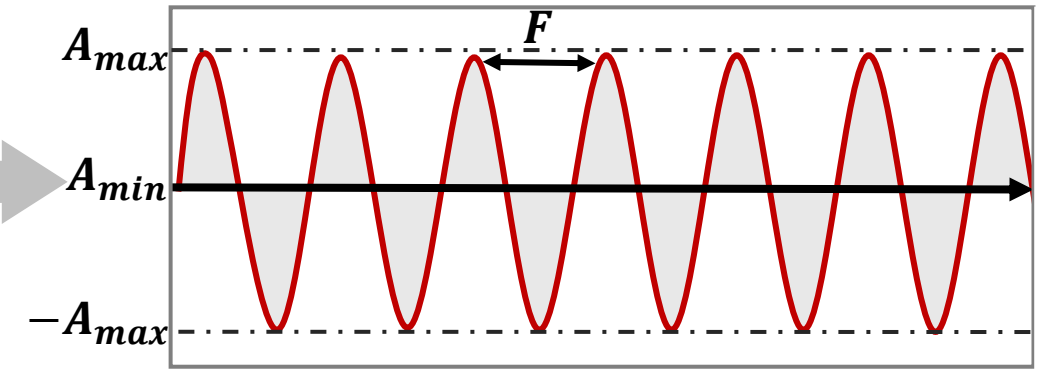
$$A * sin(2\pi Ft + \phi)$$

Sensor Type [Accel/Gyro]

Amp. = [A_{min}, A_{max}]

Freq. = [0, 50]kHz

Sensor Profile



Generated Sensor Signal

Mission Mutation

- Generates diverse 3D mission paths.

Dist. = [0,30]m.

XY-Ang.= [0,360]°

Z-Ang.= [-90,+90]°

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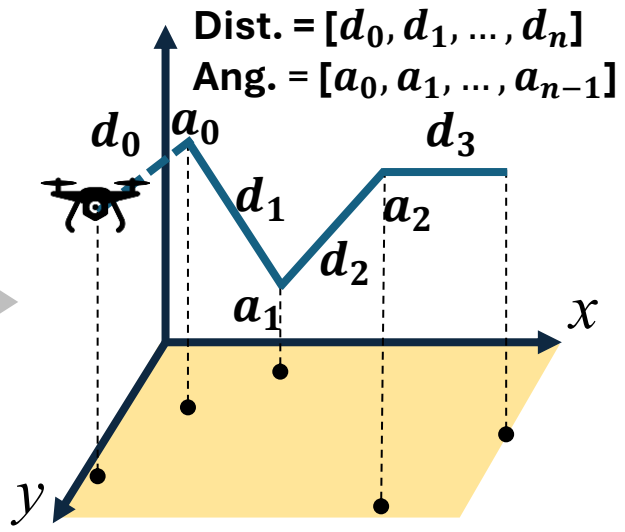
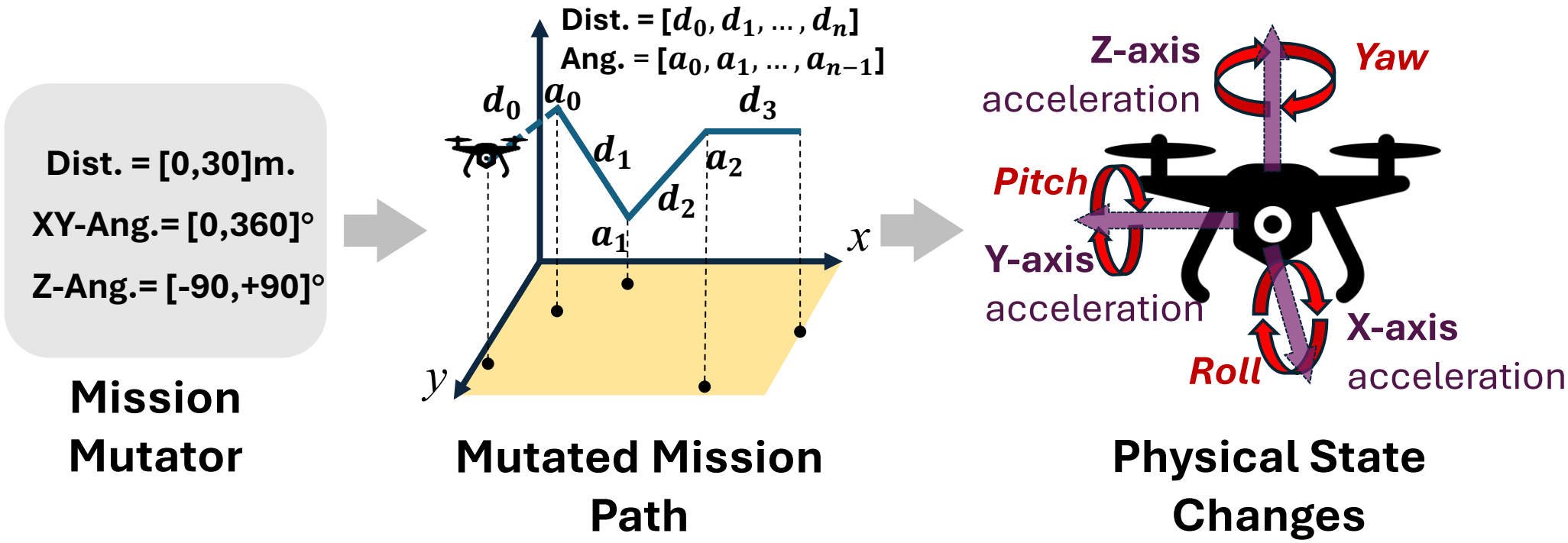


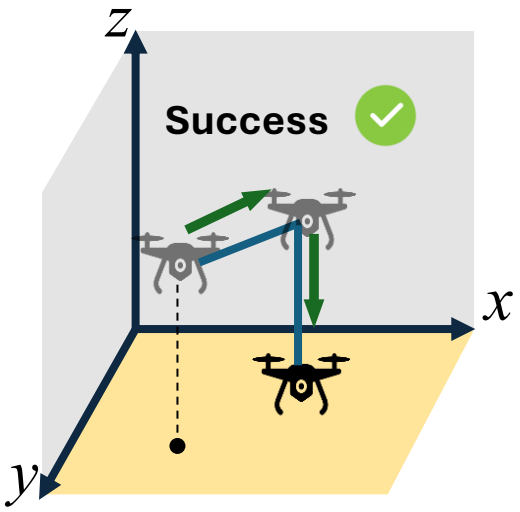
Mutated Mission Path

Mission Mutation

- Generates diverse 3D mission paths.



Mission Failure Detection



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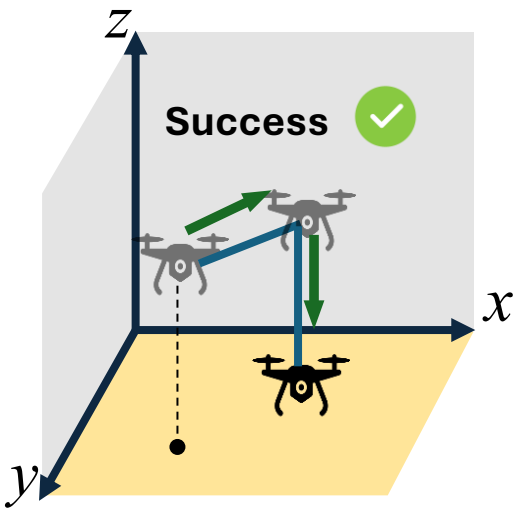

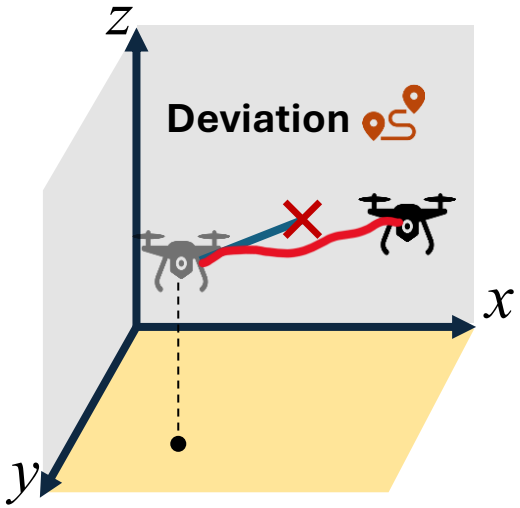

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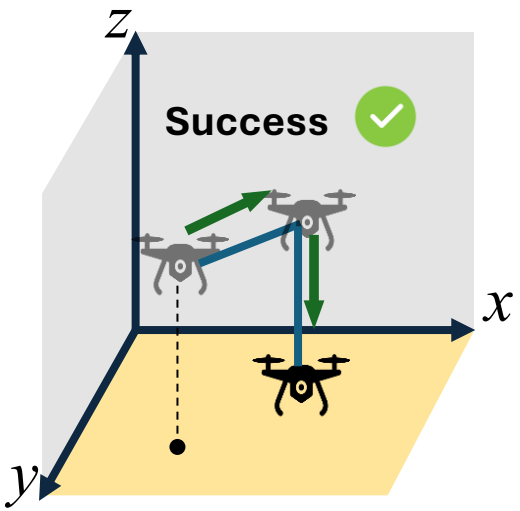

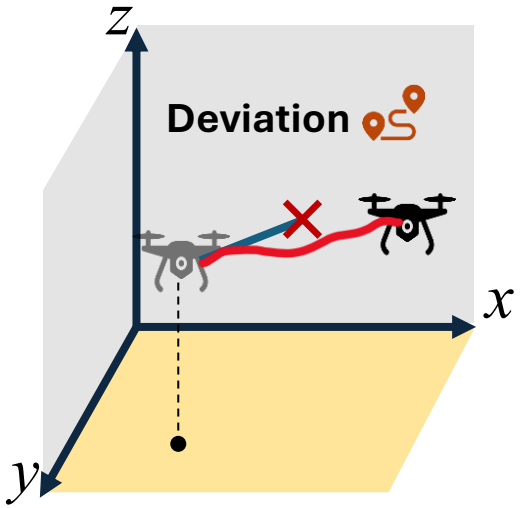

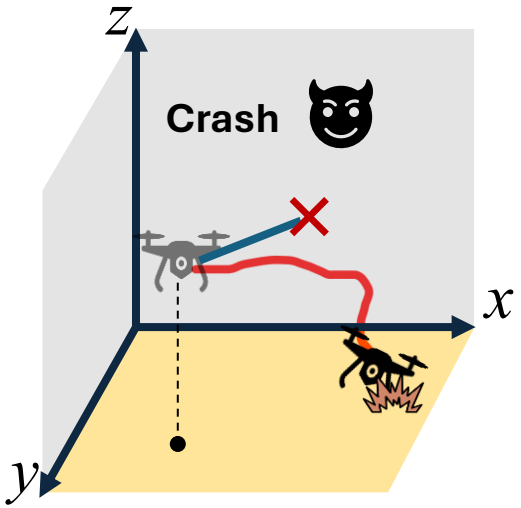

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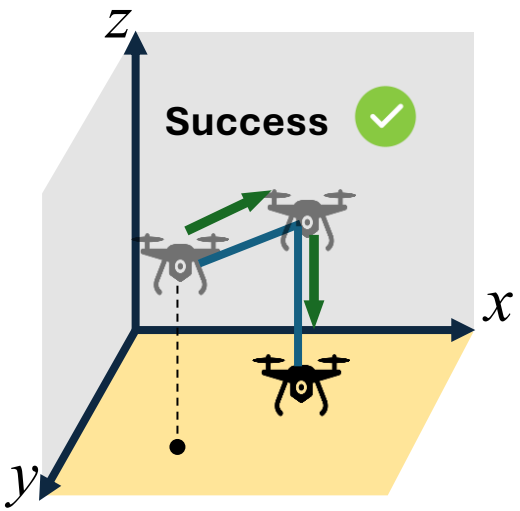

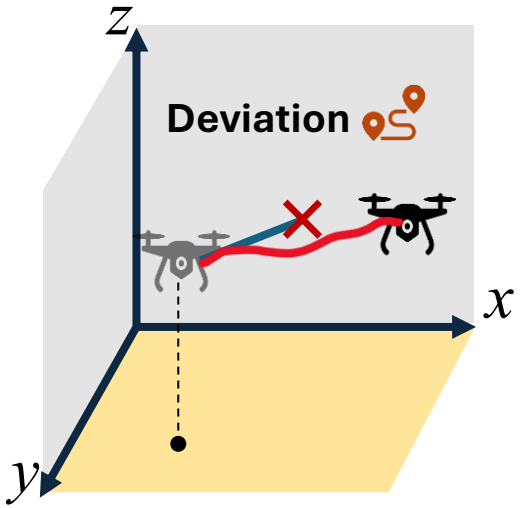

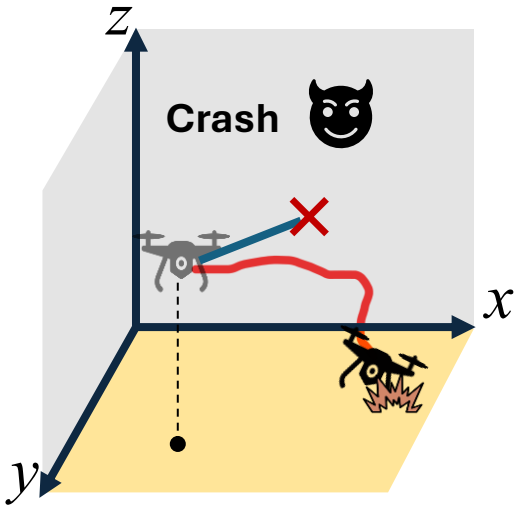

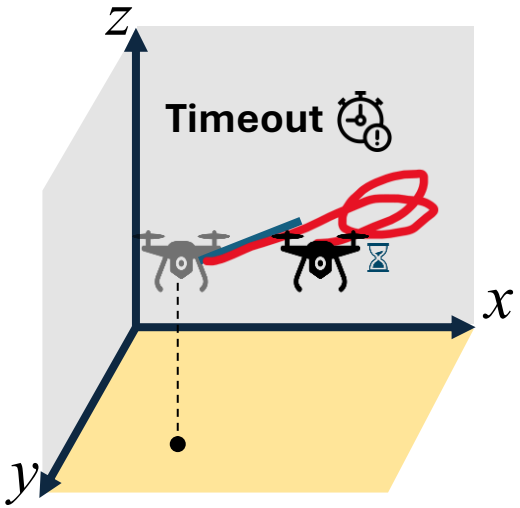

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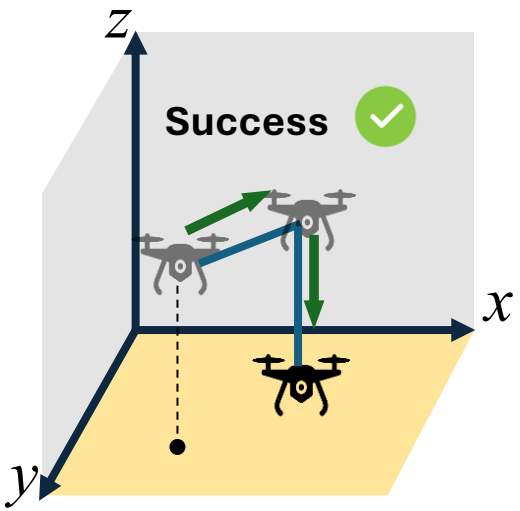

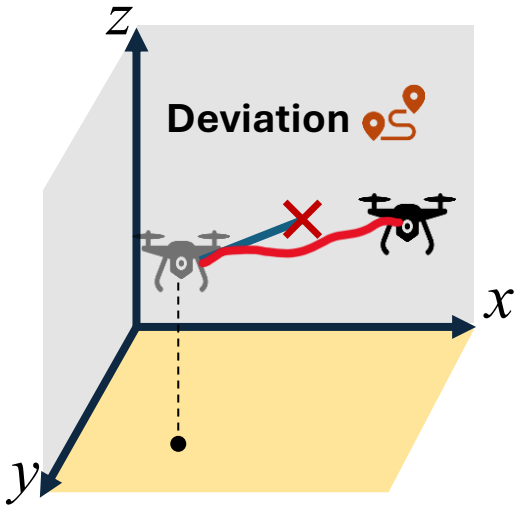

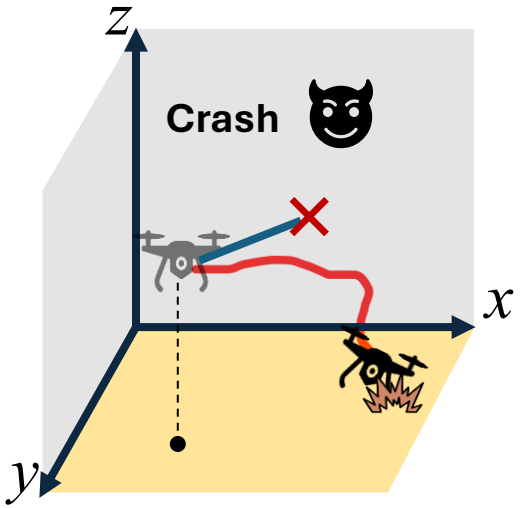

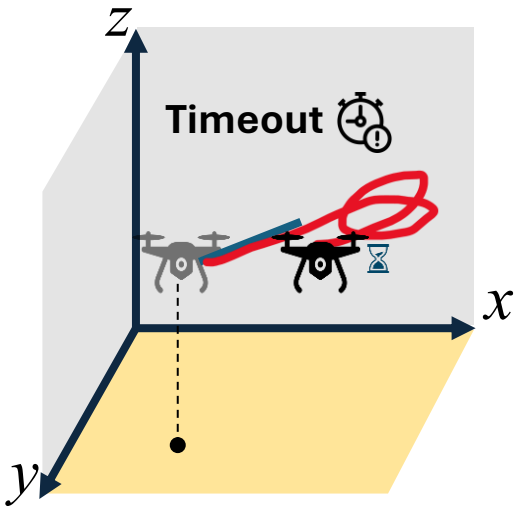

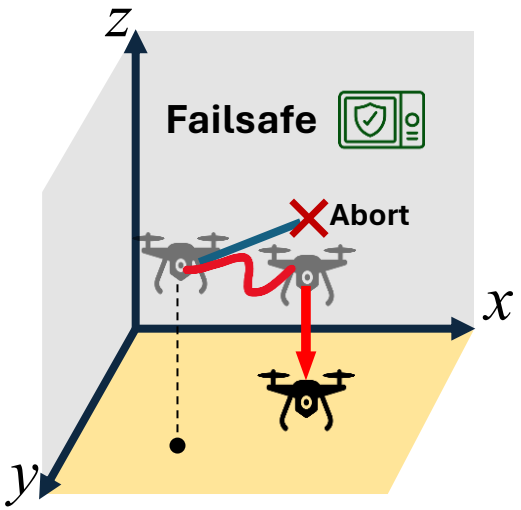

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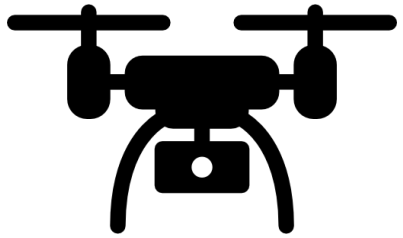

Mission Success ≠ Stable Flight

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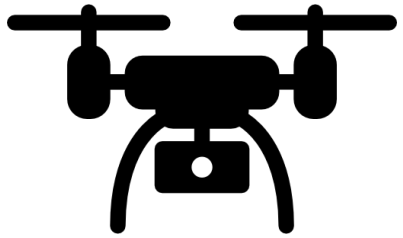

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Code Coverage ≠ More Attacks

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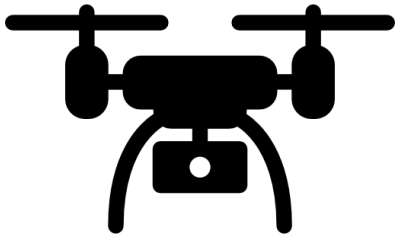

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Feedback Metric: Resilience Score

Resilience Score

- Quantifies RAV **stability and performance**.

- Having lower ρ → weaker RAV resilience (system destabilized).

Resilience Score

- Quantifies RAV **stability and performance**.

- Having lower ρ → weaker RAV resilience (system destabilized).

Computed by monitoring **internal controller states**:

1. Acceleration
2. Angular Velocity
3. Position

Evaluation

- ArduCopter v4.5.0

- Physical drone experiments with Pixhawk4 board.

Sensor Profiles Used by IMUFuzzer

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6 real-world IMU sensor profiles

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6 real-world IMU sensor profiles

Find a **valid range** of displacements for each IMU under test.

	Sensor	Amp. (V)	Freq. (KHz)	Displacement	
				Min	Max
Accel.	AXDL345	10.3	3.8	-134.0	53.2
	MPU-6050	9.5	5.3	-80.0	80.0
	MPU-9250	4.2	20.6	-22.2	-4.3
Gyro.	L3G4200D	8	8.1	-105.1	105.3
	MPU-6050	3.2	26.86	-270.4	260.3
	MPU-9250	3.2	27.3	-232.6	247.1

Attacks Discovered

23 unique attacks across accelerometers and gyroscopes

- Each case had:
  - distinct **flight path**.
  - distinct **acoustic signal.**
- *19 cases* resulted in the RAV *crashing*.
- *4 cases* made the RAV suffer significant *deviation*.

Statefulness of Attacks

#	Attk. ID	Signal Injection		
		Amp.	Freq. (kHz)	Sensor Profile
1	A1	19.75-29.75	20	AXDL345
2	A2	19.25-29.50	16	AXDL345
3	A3	9.25-11.00	40	MPU-6050
4	A4	13.25-19.25	28	MPU-6050
5	A5	18.5-23.50	11.2	MPU-6050
6	A6	20.25-28.25	16	AXDL345
7	A7	10.00-26.75	40	MPU-6050
8	A8	17.50-19.50	24	MPU-6050
9	A9	4.25-8.50	52	AXDL345
10	A10	15.00-22.50	28	AXDL345
11	A11	2.75-8.00	44	AXDL345
12	A12	14.00-29.50	47.2	AXDL345
13	G1	13.50-30.00	35.4	MPU-6050
14	G2	7.25-30.00	48	L3G4200D
15	G3	9.00-29.00	48	MPU-6050
16	G4	7.25-30.00	40	L3G4200D
17	G5	20.25-29.75	23.8	L3G4200D
18	G6	11.00-17.00	6.4	MPU-9250
19	G7	27.25-29.75	15.8	MPU-9250
20	G8	22.50-28.75	47.8	MPU-6050
21	G9	17.50-29.75	23.9	MPU-9250
22	G10	22.25-30.00	8.3	MPU-6050
23	G11	17.00-18.50	29.8	MPU-9250

Statefulness of Attacks

Only **7 attacks** worked in **all flight scenarios.**

Other **16 attacks** required **specific physical states.**

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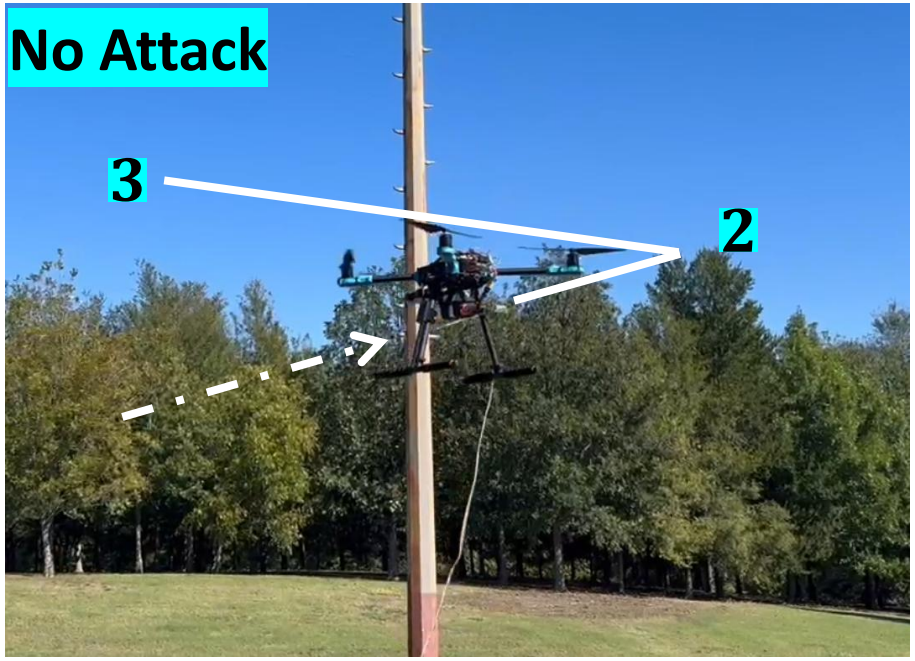
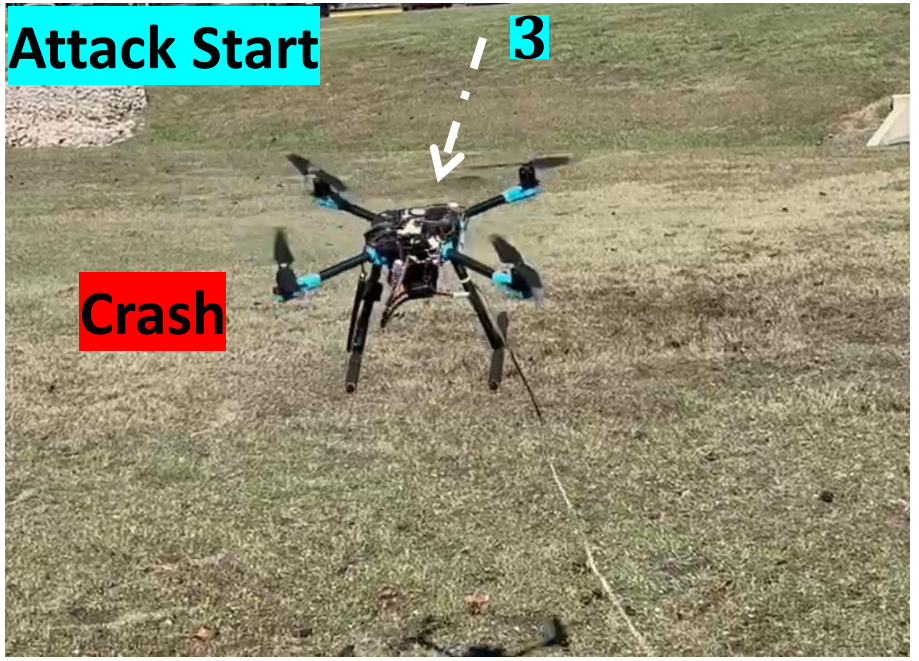
4	A4	13.25-19.25	28	MPU-6050
5	A5	18.5-23.50	11.2	MPU-6050
6	A6	20.25-28.25	16	AXDL345
7	**A7**	**10.00-26.75**	**40**	**MPU-6050**
8	**A8**	**17.50-19.50**	**24**	**MPU-6050**
9	**A9**	**4.25-8.50**	**52**	**AXDL345**
10	**A10**	**15.00-22.50**	**28**	**AXDL345**
11	A11	2.75-8.00	44	AXDL345
12	A12	14.00-29.50	47.2	AXDL345
13	**G1**	**13.50-30.00**	**35.4**	**MPU-6050**
14	G2	7.25-30.00	48	L3G4200D
15	G3	9.00-29.00	48	MPU-6050
16	G4	7.25-30.00	40	L3G4200D
17	G5	20.25-29.75	23.8	L3G4200D
18	**G6**	**11.00-17.00**	**6.4**	**MPU-9250**
19	G7	27.25-29.75	15.8	MPU-9250
20	G8	22.50-28.75	47.8	MPU-6050
21	G9	17.50-29.75	23.9	MPU-9250
22	**G10**	**22.25-30.00**	**8.3**	**MPU-6050**
23	G11	17.00-18.50	29.8	MPU-9250

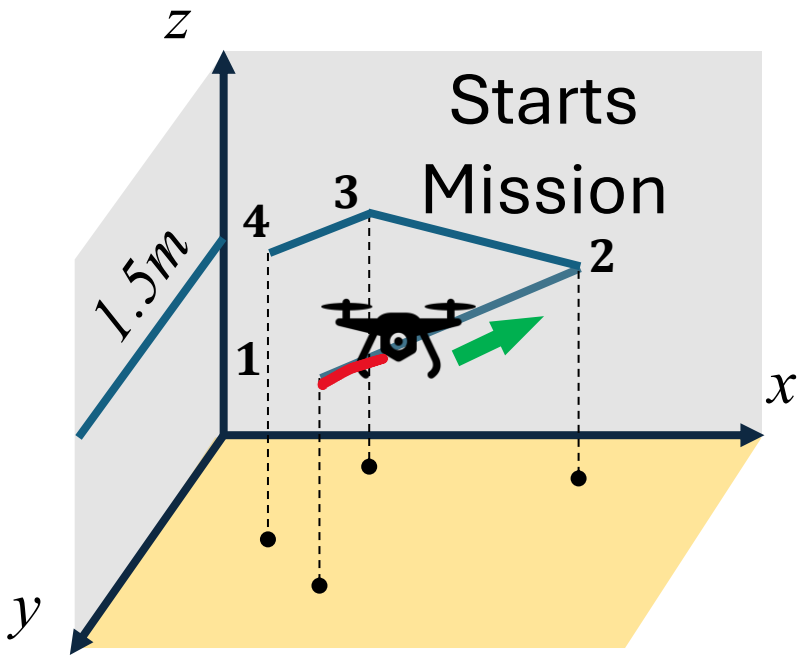
Real-world Experiments

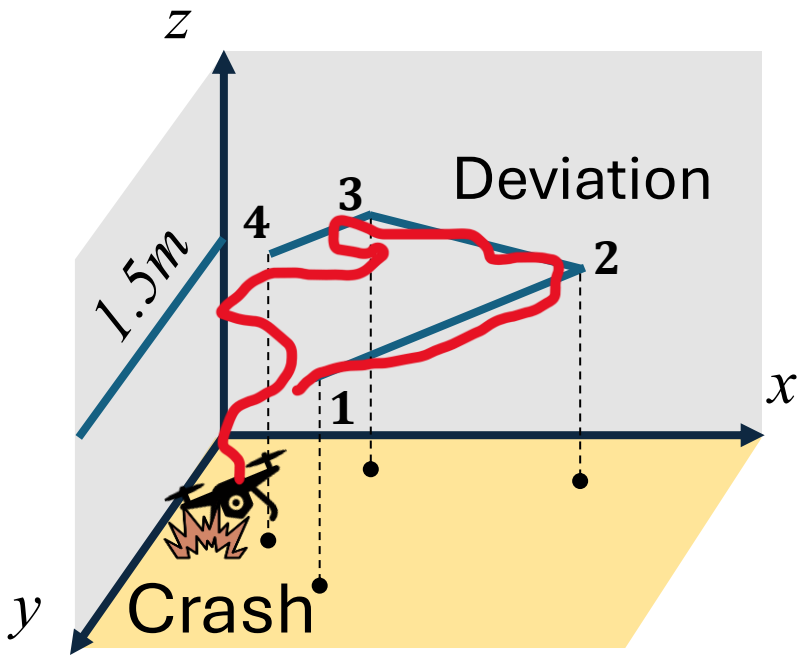
- Physical Experiments:
  - Pixhawk4 drone with Ardupilot v4.5.
  - Mission with varied physical states.

- Inject signal at **27.4 kHz** into an **ICM-20689 gyroscope**.


No Attack
3
2

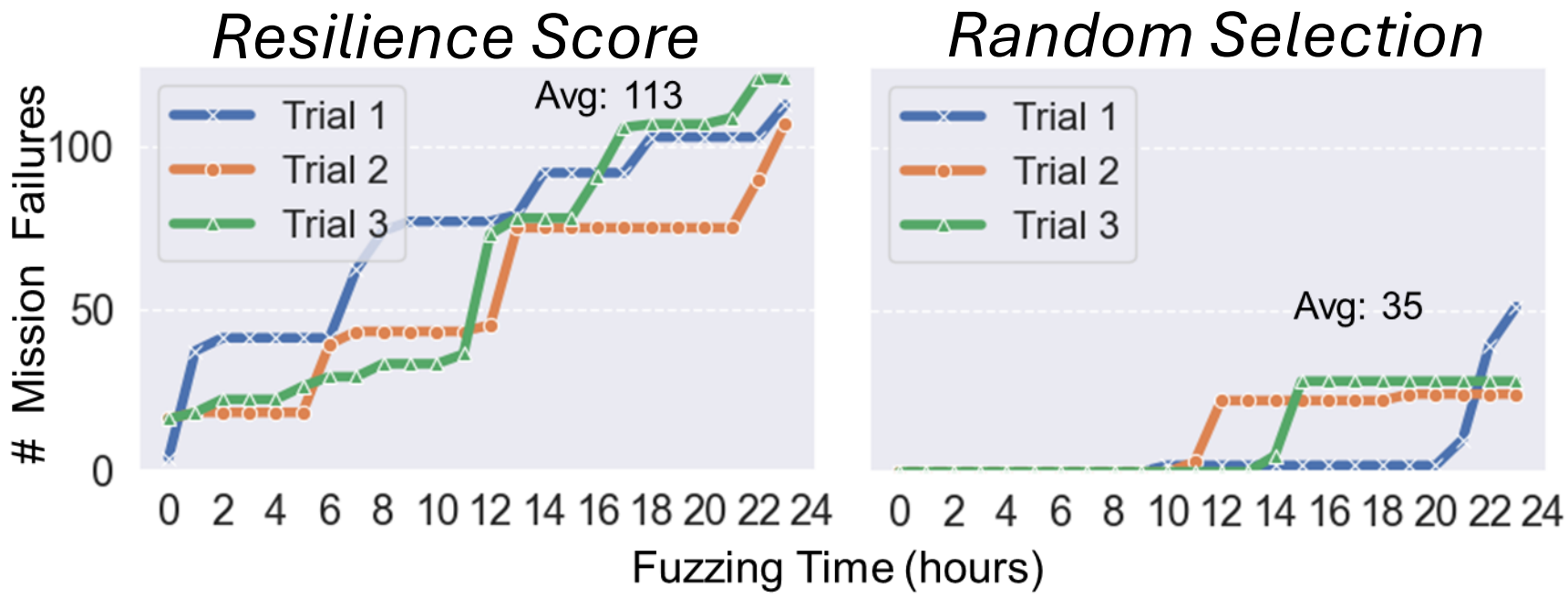

Attack Start
3
Crash


z
Starts
Mission
3
4
2
1.5m
1
x
y


z
Deviation
3
4
2
1.5m
1
x
y
Crash

Effectiveness of Resilience Feedback

- Fuzzing with and without resilience score feedback.



Effectiveness of Resilience Feedback

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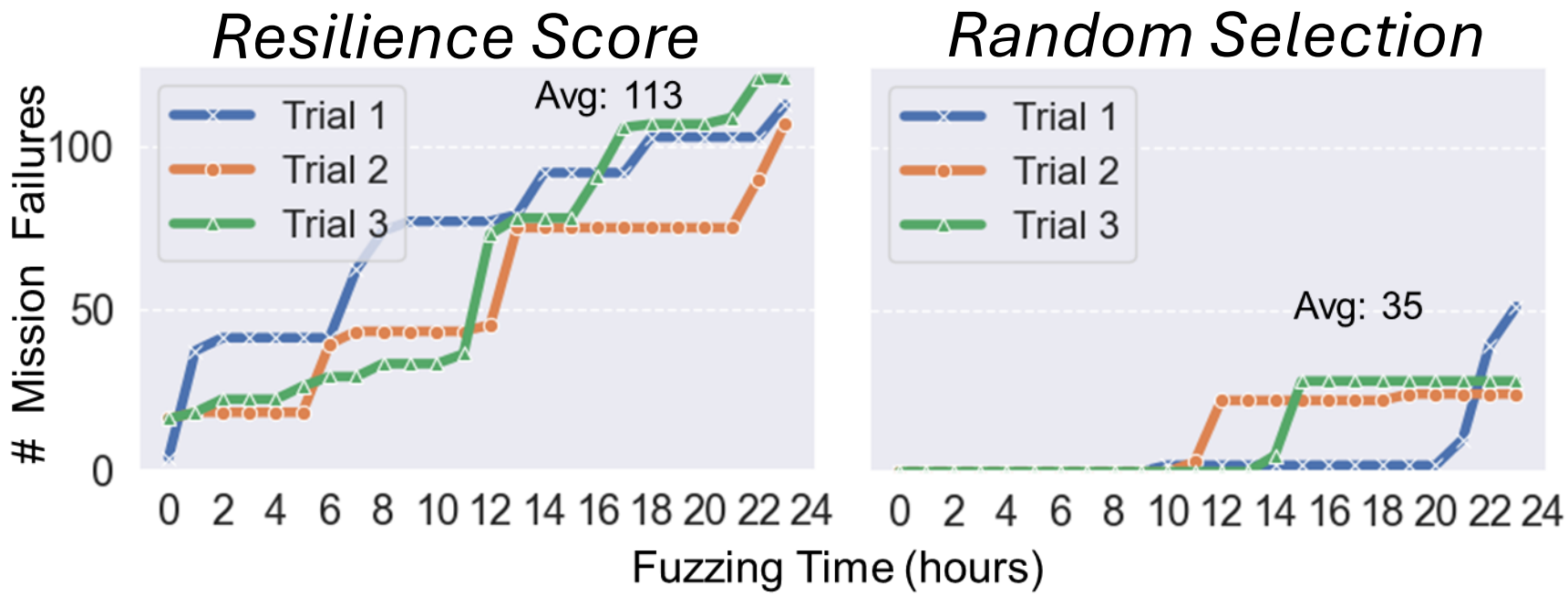
2.2x additional mission failures than randomized selection



IMUFUZZER Summary

- **Sensor fuzzing** framework to find acoustic injection attacks.
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- **23 unique attacks** with **6 real-world IMU profiles**.
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Join us at the poster session!

Q&A

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