27TH USENIX SECURITY SYMPOSIUM

Injected and Delivered: Fabricating Implicit Control over Actuation Systems by Spoofing Inertial Sensors

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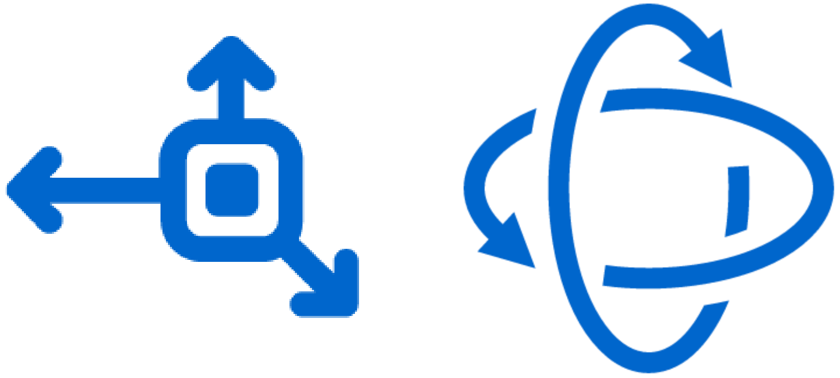
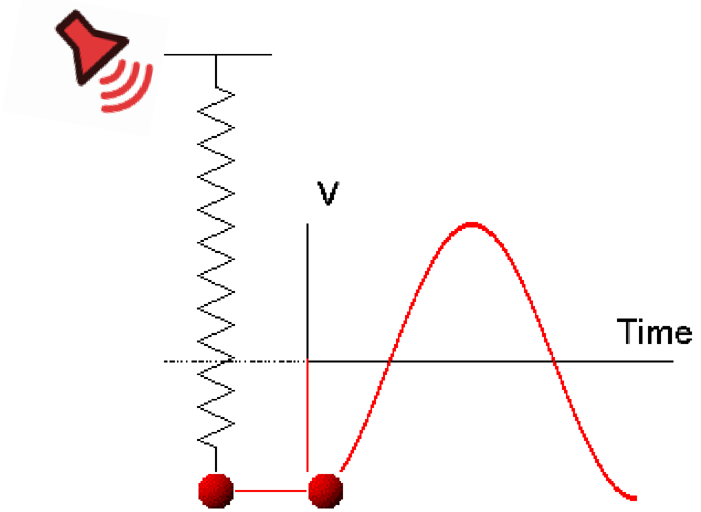
MEMS Inertial Sensors



- Provide motion feedback
  - Accelerometer: Linear acceleration
  - Gyroscope: Angular velocity
- **Miniaturized** mechanical sensing structure
  - Similar to mass-spring
  - Transduce inertial stimuli to electrical signals
  - Vulnerable to ***acoustic resonance***

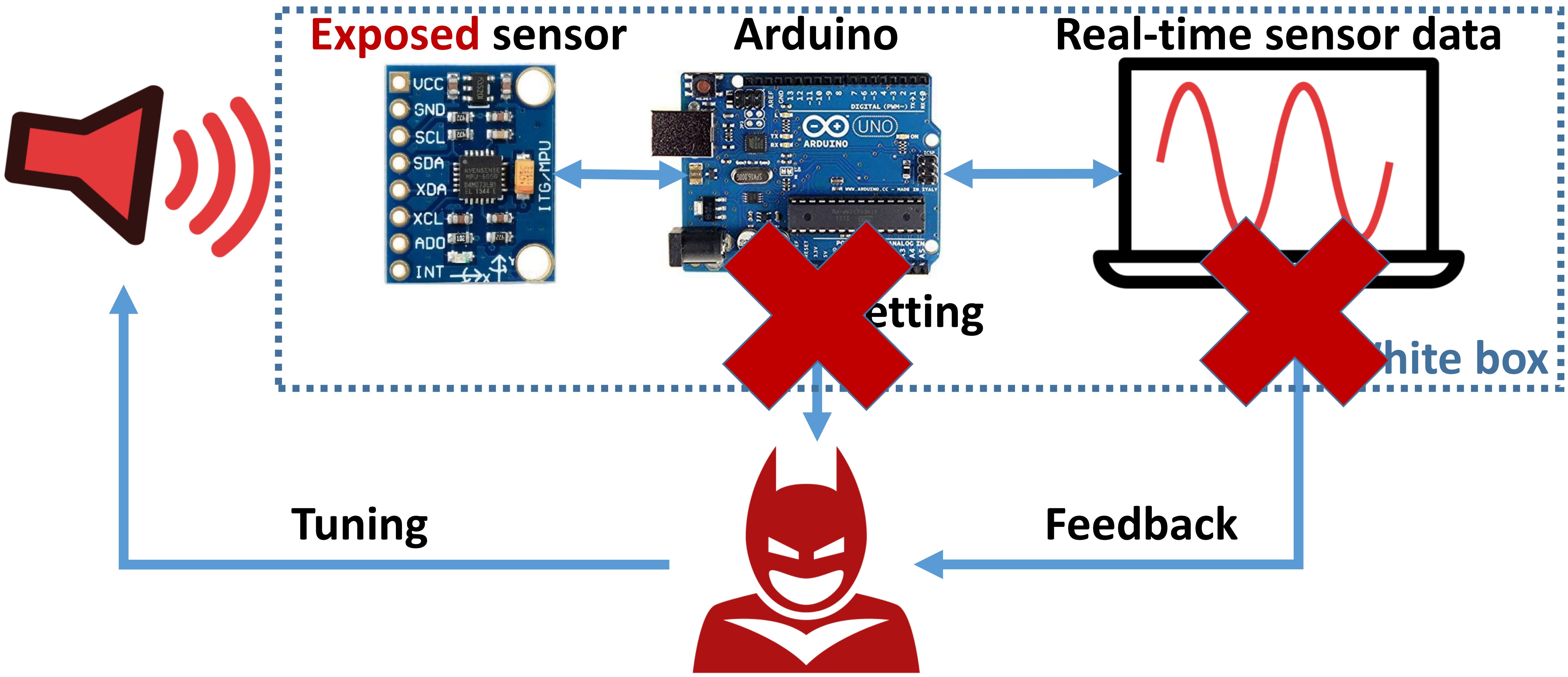


Acoustic Attacks on MEMS Inertial Sensors

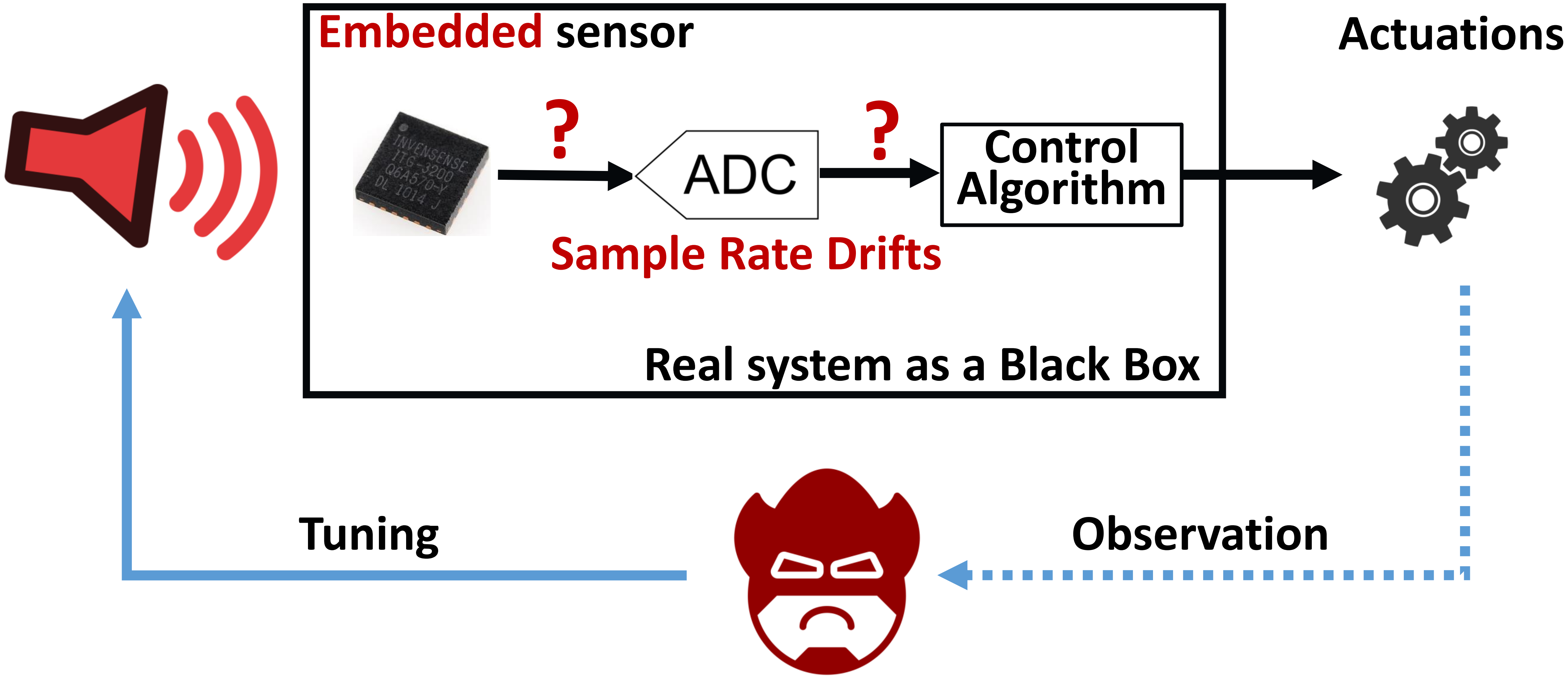
- Son et al. "**Rocking drones**" [USENIX Sec'15] [1]
  - **DoS** attack on gyroscopes

- Trippel et al. "**WALNUT**" [Euro S&P'17] [2]
  - Control **exposed** accelerometers connected to Arduino (**white box**)
  - Sample rate drifts
    - *"This limits an attacker's ability to achieve control over a sensor's output for more than 1–2 seconds*[2]*"*

White-box approach



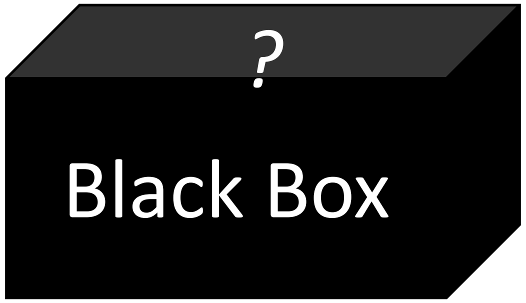
Motivation: A Real System is often a Black Box



Problem

How to ***non-invasively*** control output of ***embedded*** inertial sensors despite the sample rate drifts?

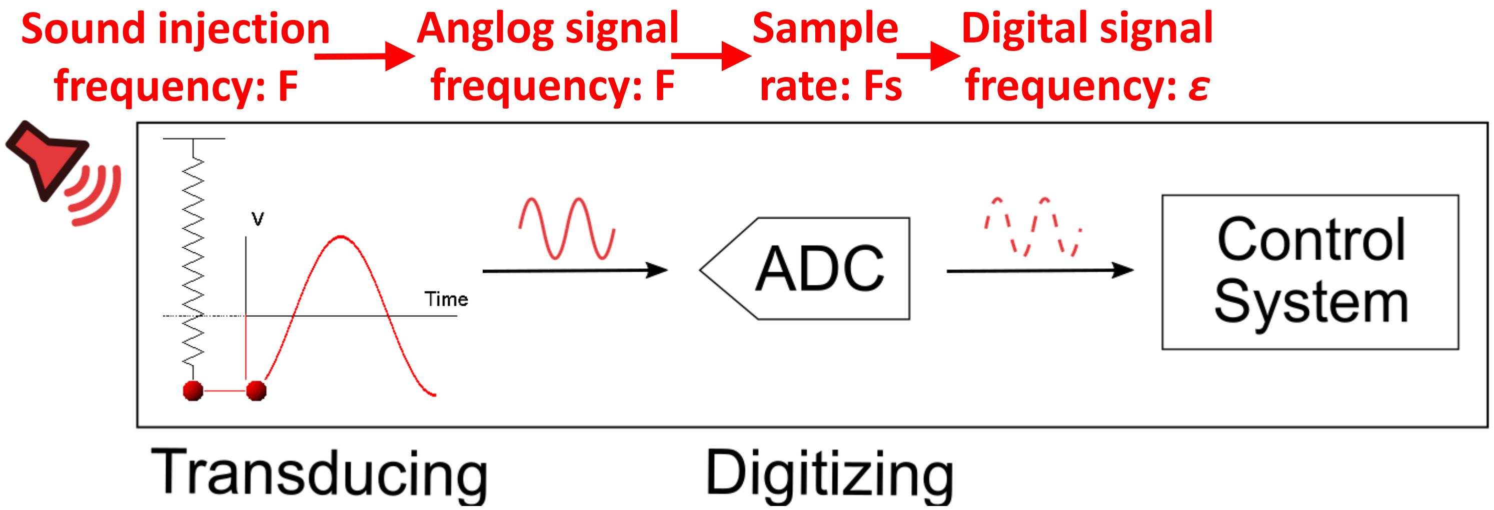
(***Black box*** approach)



Contributions

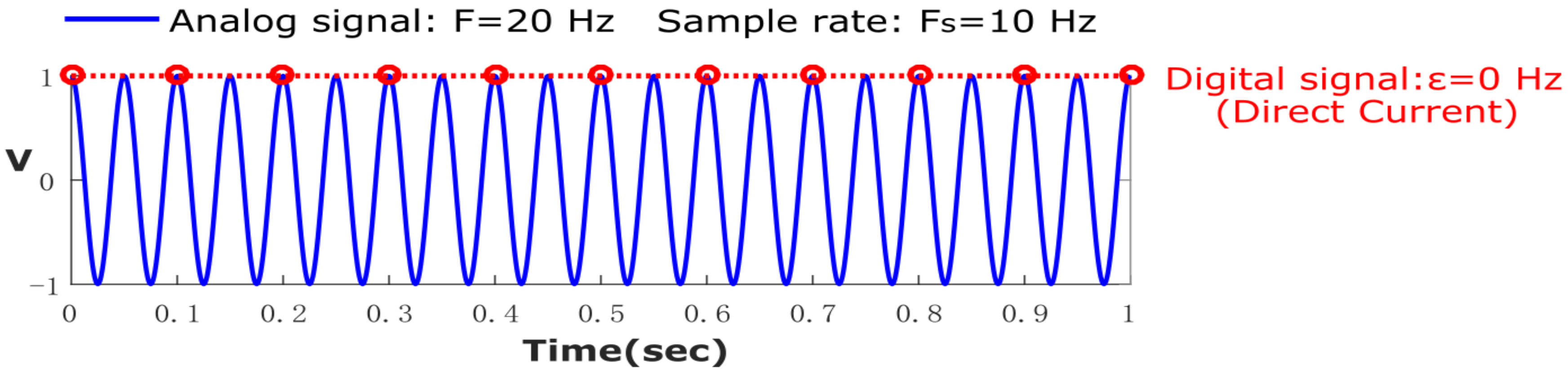
- **Theoretical results:**
  - Sample rate drifts amplification theorem
  - Two new methods: *Digital amplitude adjusting* and *Phase Pacing*
- ***Non-invasive*** attacks on sensors ***embedded in real systems***
  - *Side-Swing* and *Switching* attacks
  - Evaluated on 25 devices
  - Demonstrate implicit control over different kinds of systems
- ***Automatic*** attacks with feedback
- Attacks using ***non-resonant*** frequencies

Acoustic Injection

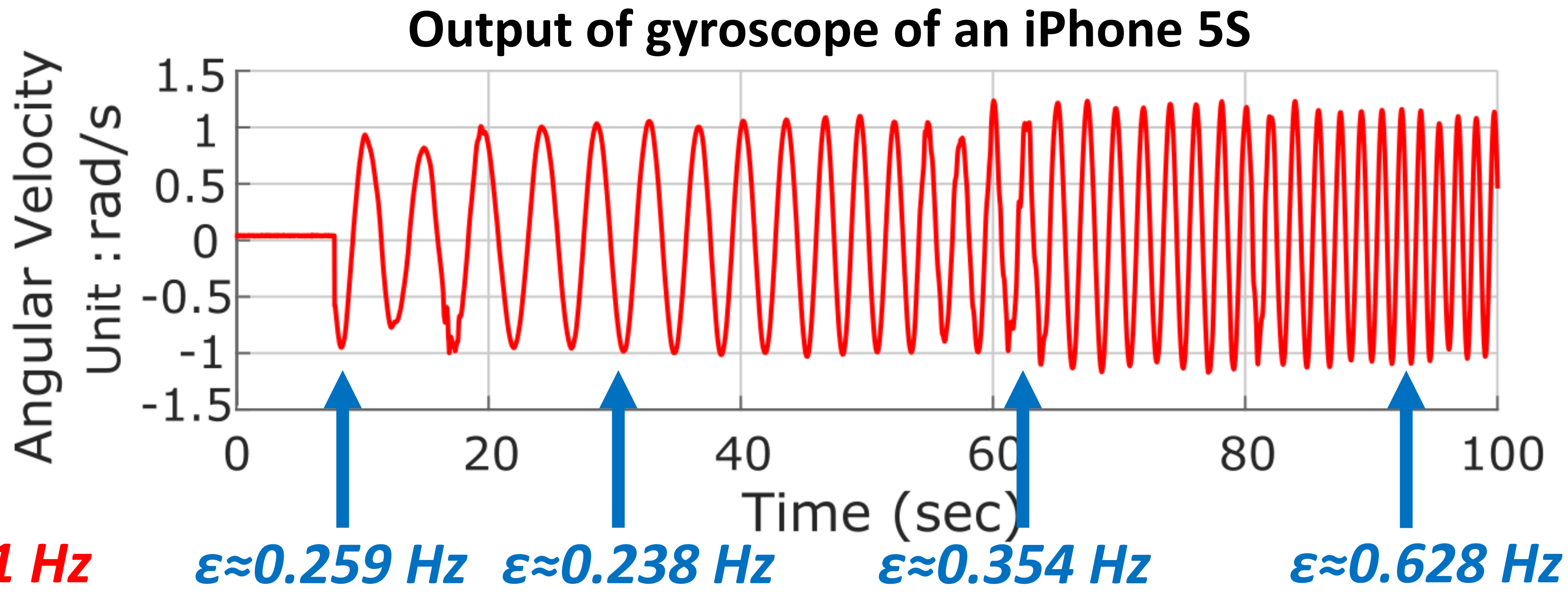


- ***Undersampling*** (*F > Fs/2*)
  - ***Aliasing***
  - When *F = nFs*, we have *ε = 0* (**Direct Current**, DC)

$$F = n \cdot F_S + \epsilon \quad \left(-\frac{1}{2}F_S < \epsilon \le \frac{1}{2}F_S, n \in \mathbb{Z}^+\right) \quad (3)$$



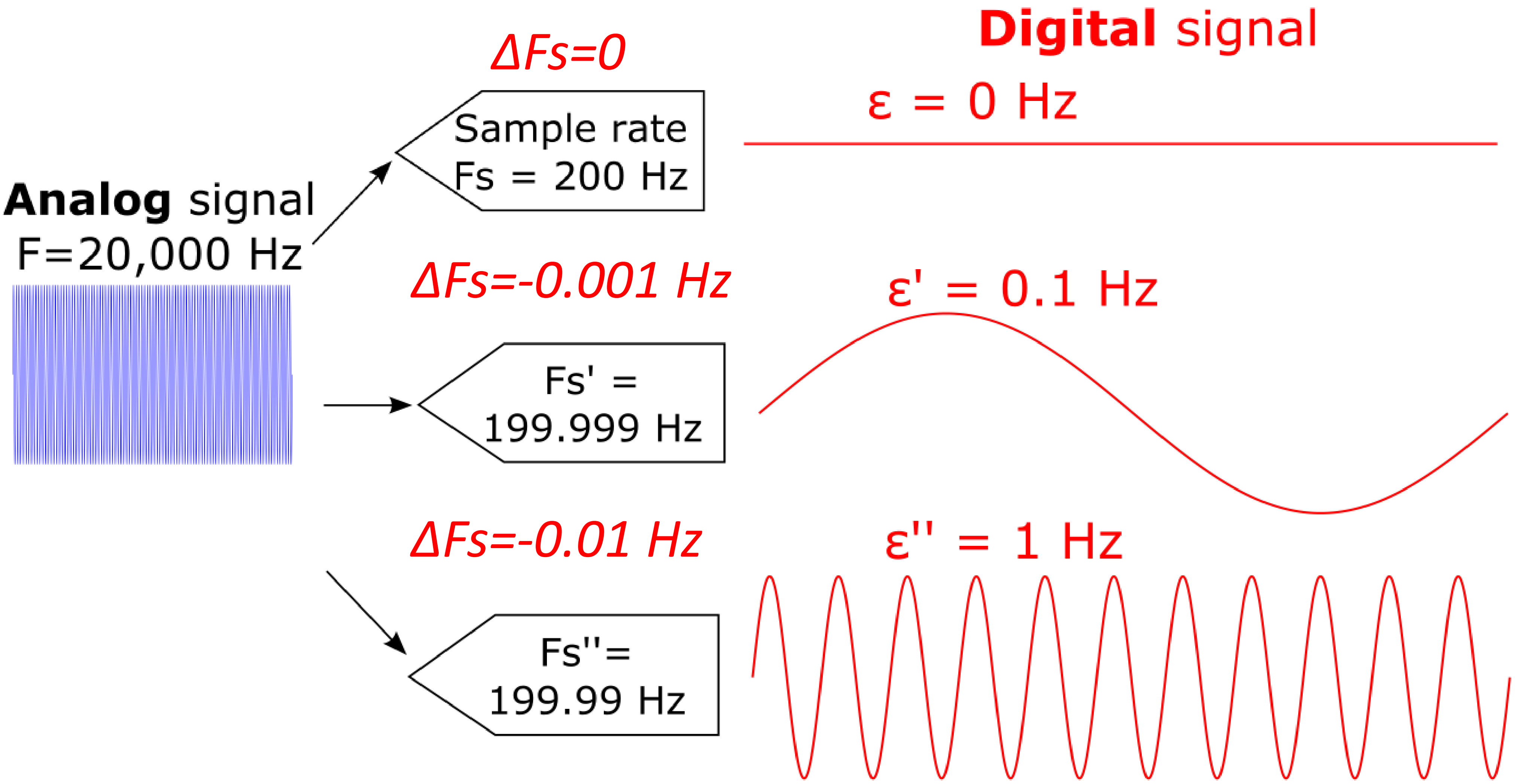
Amplification Effects of Sample Rate Drifts



$$F = n \cdot F_S + \varepsilon \quad \left(-\frac{1}{2}F_S < \varepsilon \leq \frac{1}{2}F_S, n \in \mathbb{Z}^+\right) \qquad (3)$$

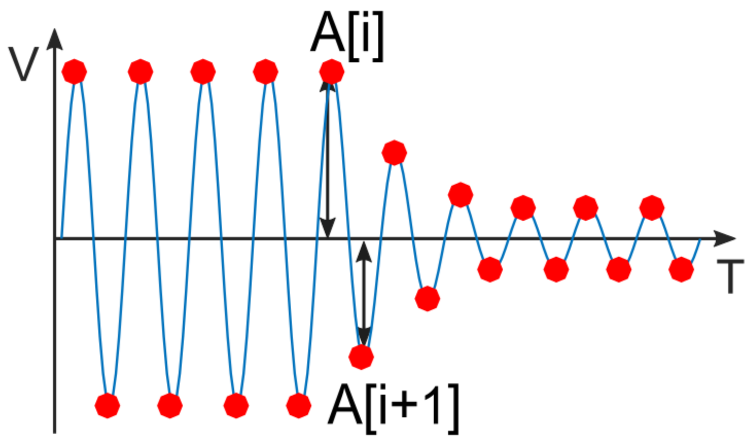
- F remains the same, but ε is deviating
- Cause: ***Fs is drifting***

Sample Rate Drifts Amplification Theorem



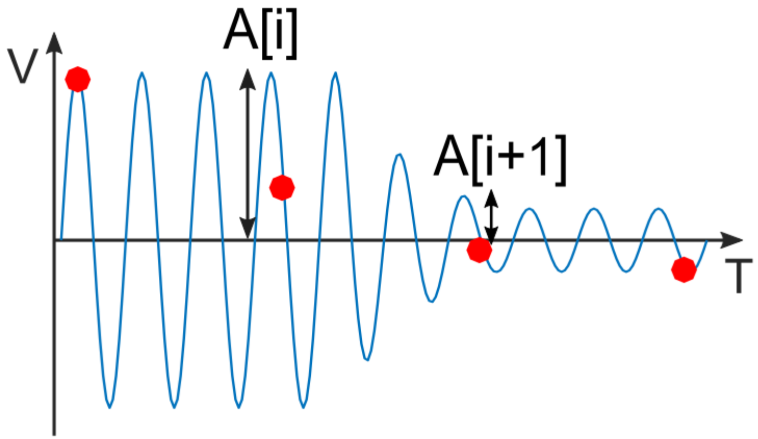
Digital Amplitude Adjusting

Sampled Correctly



A[i] and A[i+1] are correlated

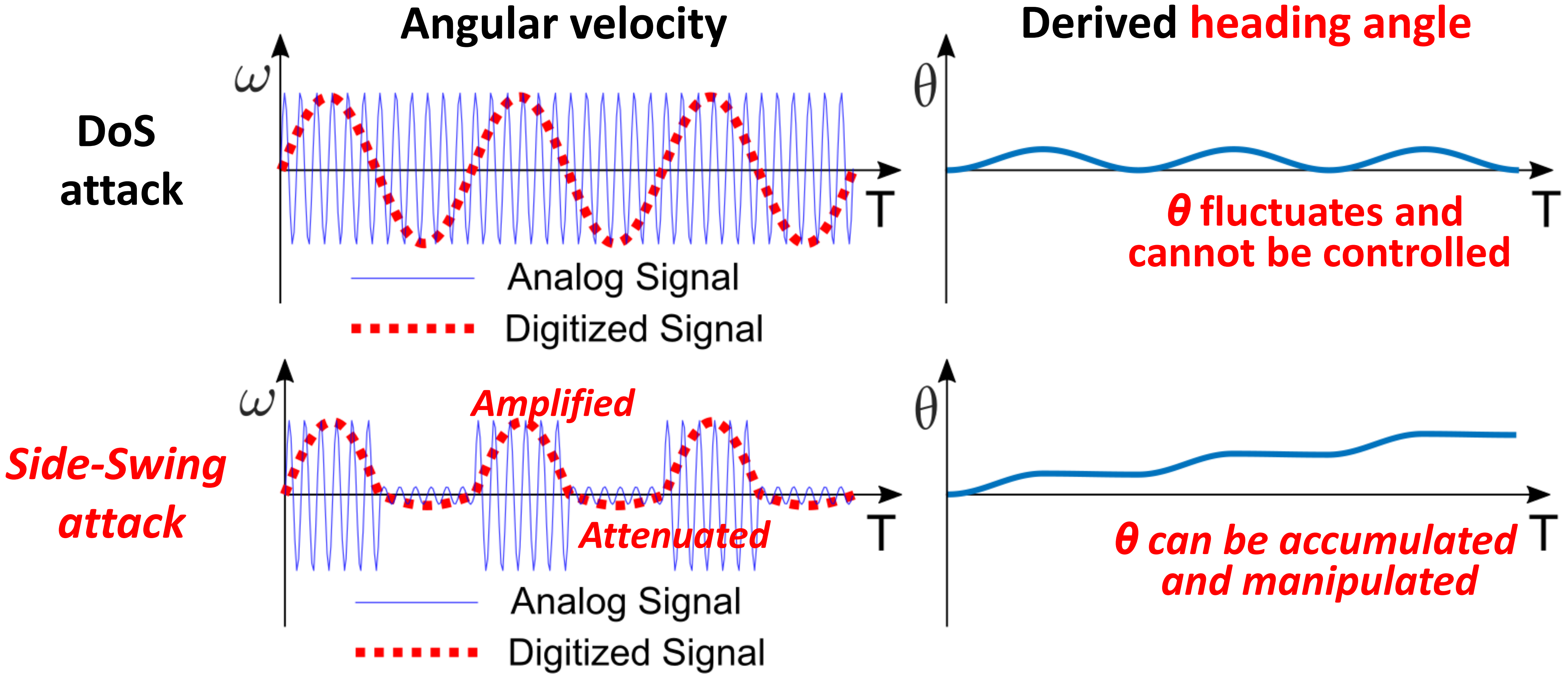
Undersampled



A[i] and A[i+1] are independent

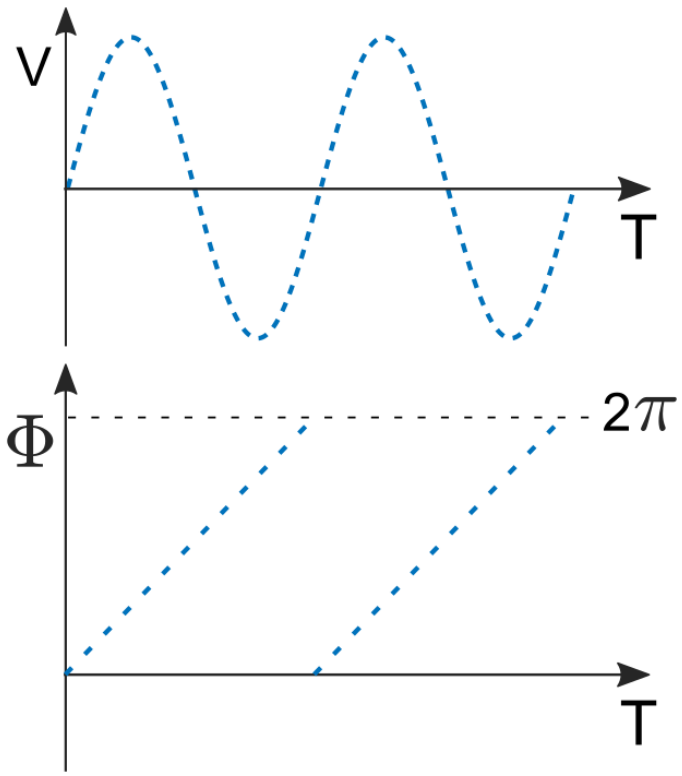
- **Undersampling** causes signal distortions
- Fabricate specific waveforms instead of oscillating sine wave

Side-Swing Attacks

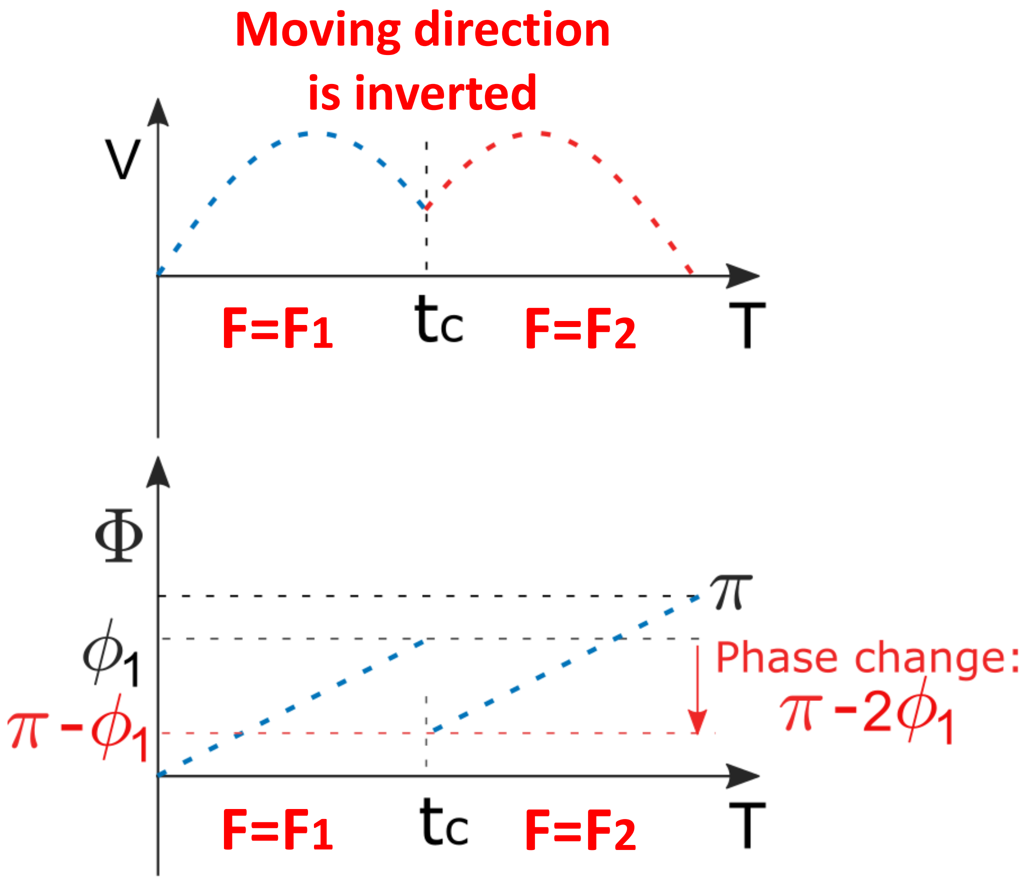


- Increase *A[i]* to amplify the induced output in the target direction
- Decrease *A[i]* to attenuate the output in the opposite direction

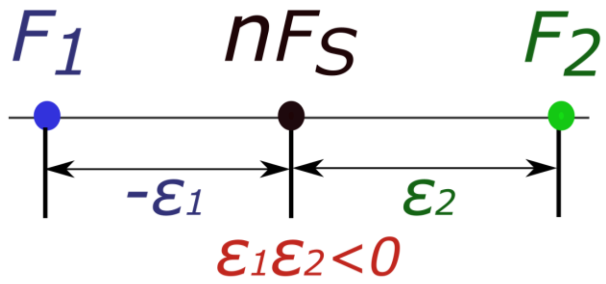
Phase Pacing



Without Phase Pacing



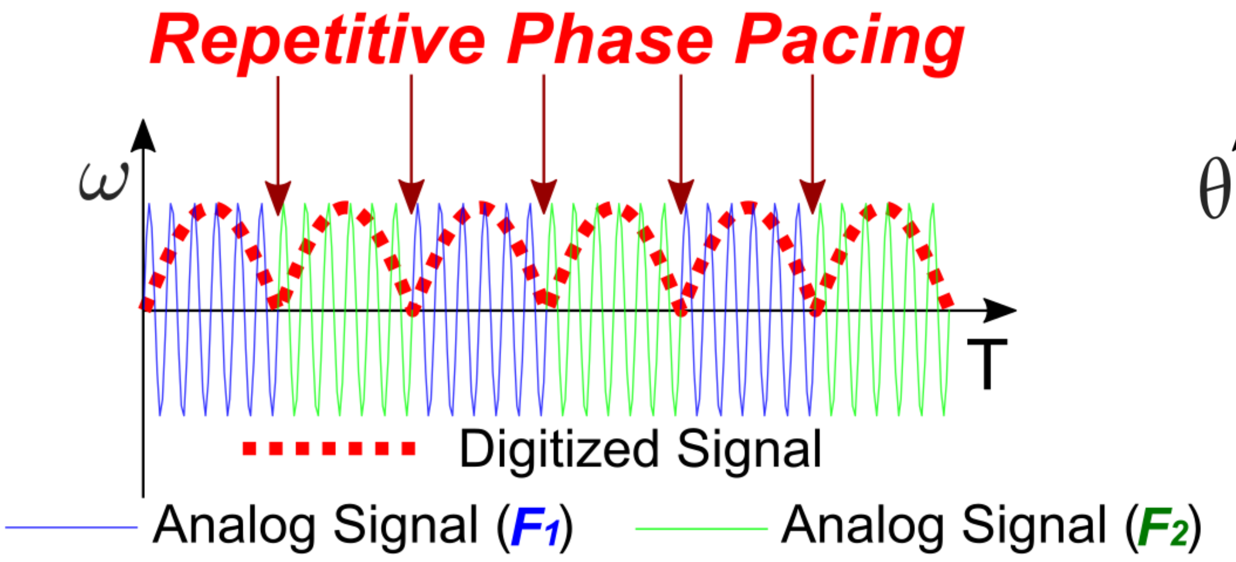
With Phase Pacing



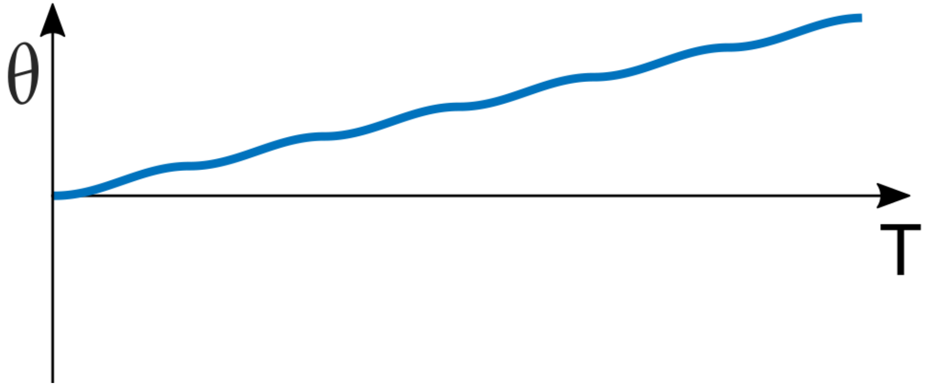
Condition of Phase Pacing

Ex: $nF_S = 20000, F_1 = 19999Hz, F_2 = 20001Hz$

Switching Attacks



Angular velocity



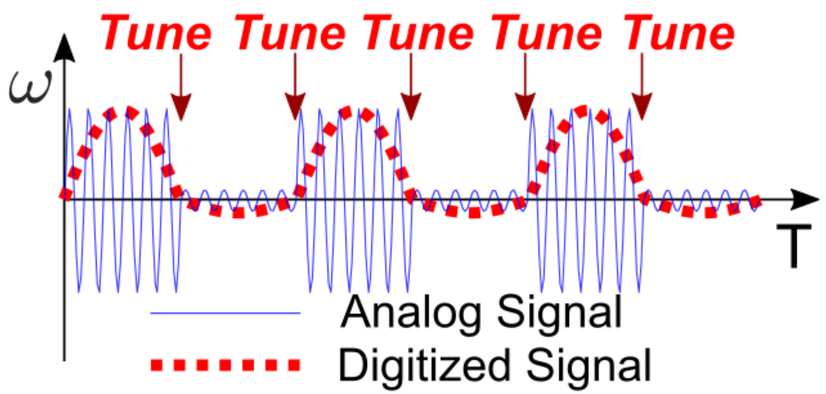
Derived heading angle

- **Repetitive *Phase Pacing***
  - Switch *F* between *F1* and *F2* back and forth

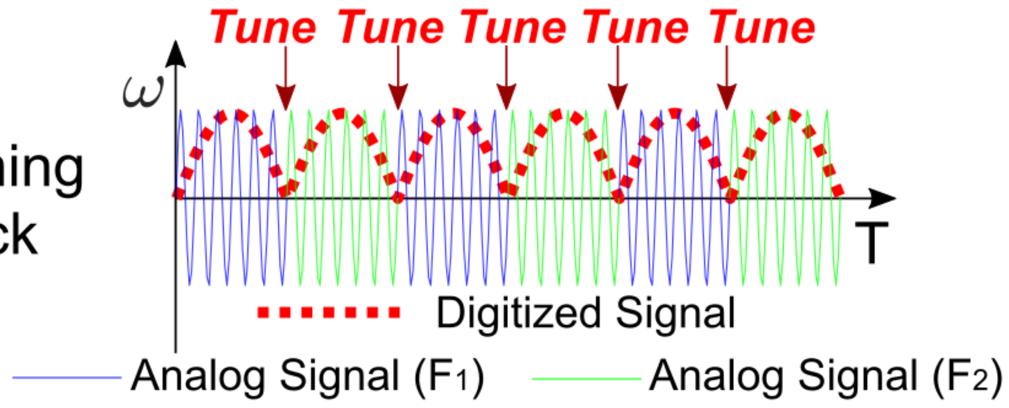
Challenges in the Black-box Approach

- Problem: Tuning time selection

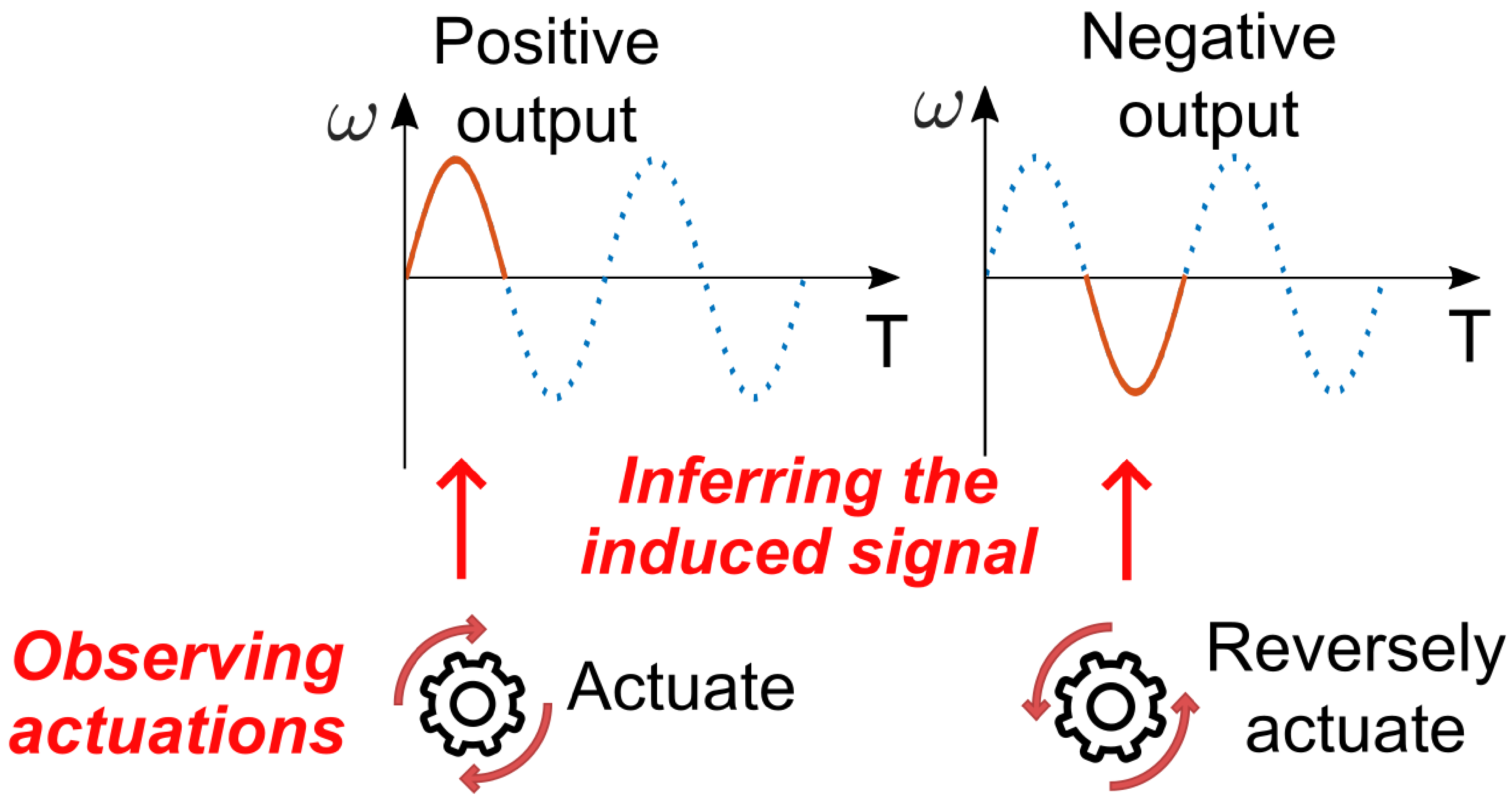
Side-Swing attack



Switching attack

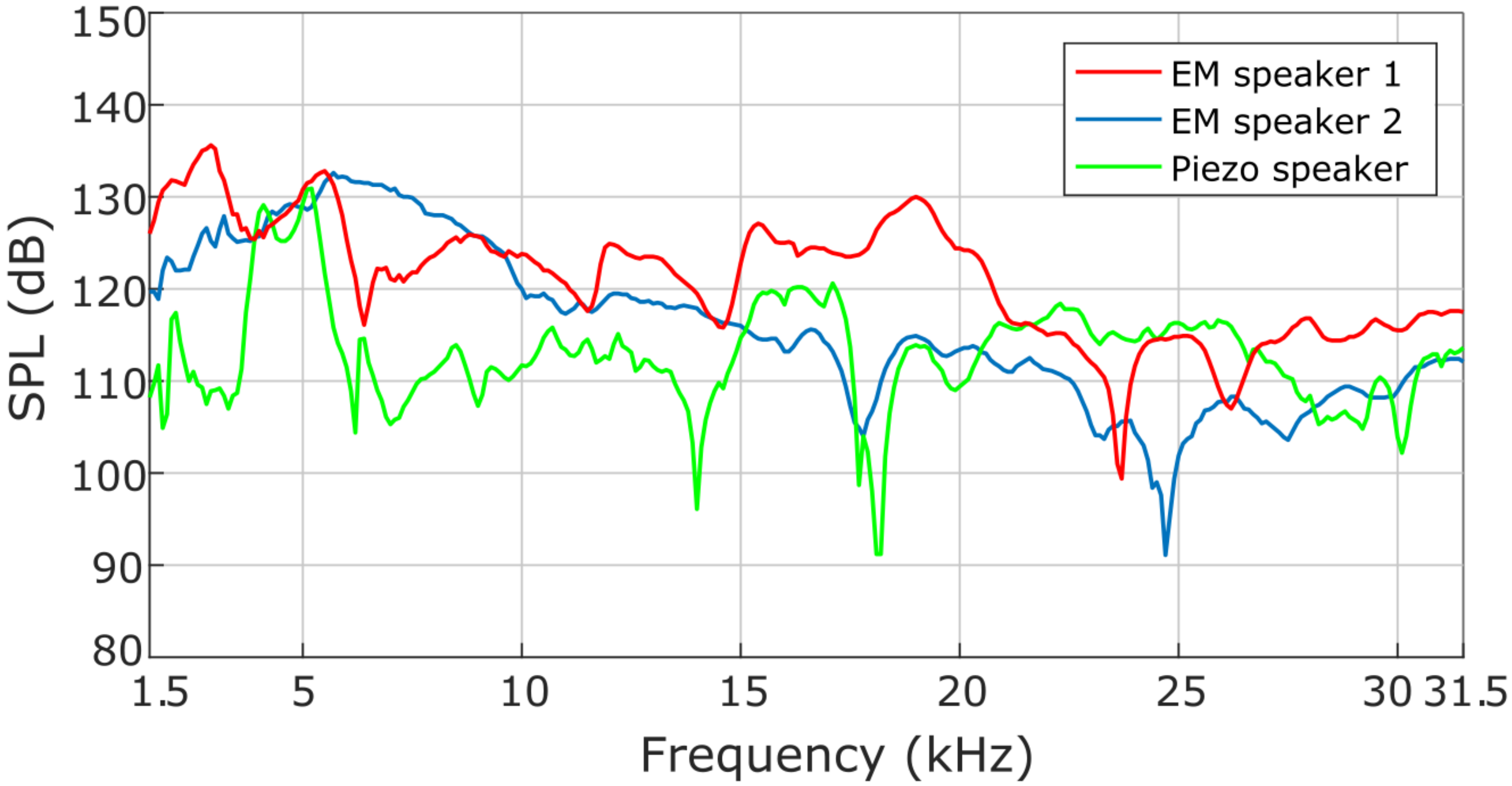


Reverse Signal Mapping



Experimental Setup

- **Sound source**
  - Sound Pressure Level
    - ***120 – 130 dB (<21 kHz)***
    - ***110 – 120 dB (>21 kHz)***
  - **50-Watt** audio amplifier
  - Function generator
  - Directivity horn



Closed-loop Control Systems

Table 1: Results of our attack experiments on closed-loop control systems

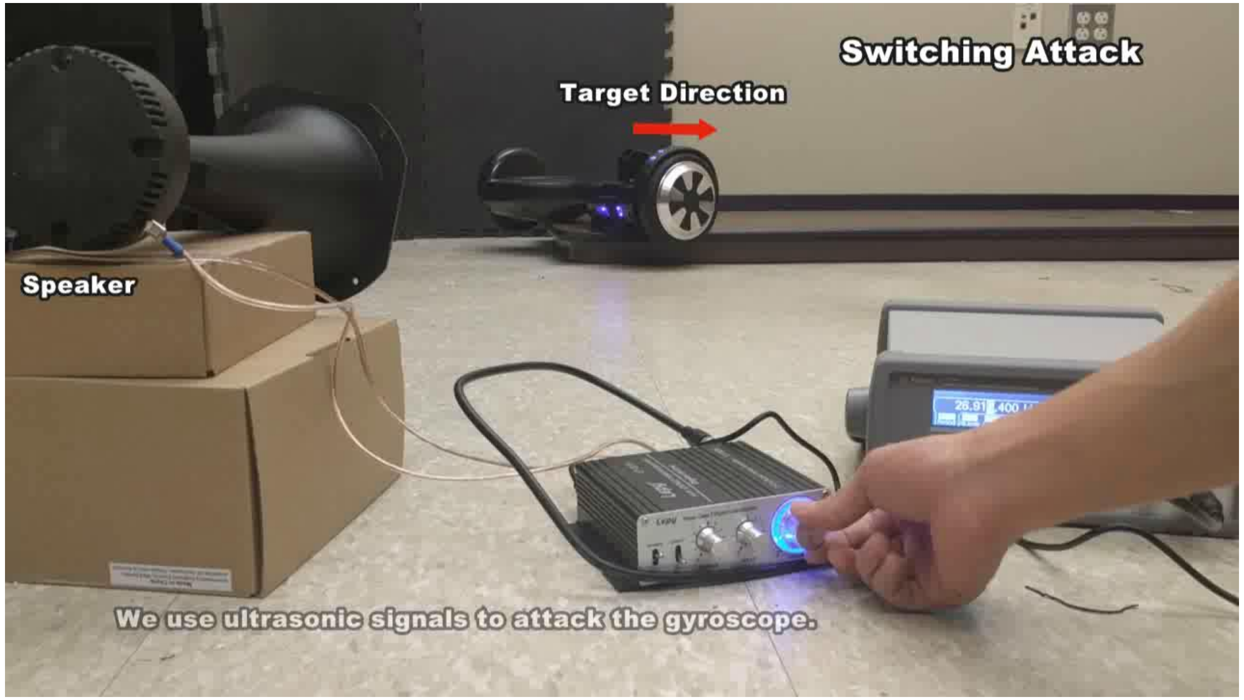
Device	Sensor		Resonant Freq. (kHz)	Affected/ Func. Axes	Max Dist. (m)	Control Level
	Type	Model†				
Megawheels scooter	Gyro	IS MPU-6050A	27.1~27.2	y/y	2.9	Implicit control
Veeko 102 scooter	Gyro	Unknown	26.0~27.2	x/x	2.5	Implicit control
Segway One S1	Gyro	Unknown	20.0~20.9	x/x	0.8	Implicit control
Segway Minilite	Gyro	Unknown	19.2~20.0	x/x	0.3	DoS
Mitu robot	Gyro	N/A SH731	19.0~20.7	x/x	7.8	Implicit Control
MiP robot	Acce	Unknown	5.2~5.4	x/x	1.2	DoS
DJI Osmo stabilizer	Gyro	IS MP65	20.0~20.3	x,y,z/x,y,z	1.2	Implicit control
WenPod SP1 stabilizer	Gyro	IS MPU-6050	26.0~26.9	z/y,z	1.8	Implicit control
Gyenno steady spoon	Gyro	Unknown	Not found	Unknown	N/A	Not affected
Liftware level handle	Acce	IS MPU-6050	5.1	x/x	0.1	DoS

† IS: InvenSense, N/A: Unknown manufacturer.

Closed-loop Control Systems

- **Self-balancing Transporter**
  - Side-Swing: https://youtu.be/Y1LLiyhCn9I
  - Switching: https://youtu.be/D-etuH04pms
- **Robot**
  - Side-Swing: https://youtu.be/oy3B1X41u5s
  - DoS: https://youtu.be/yDz8y_ht3Xg
- **Stabilizer**
  - Side-Swing: https://youtu.be/FDxaLUtgaCM
  - Switching: https://youtu.be/JcA_WXHrUEs
- **Anti-tremor device**
  - DoS: https://youtu.be/qNLzBMOKbnk

Switching attacks on a self-balancing transporter



Open-loop Control Systems

Table 2: Results of our attack experiments on open-loop control systems

Device	Sensor		Resonant Freq. (kHz)	Affected/ Func. Axes	Max Dist. (m)	Control Level
	Type	Model†				
IOGear 3D mouse	Gyro	IS M681	26.6~27.6	x,z/x,z	2.5	Implicit control
Ybee 3D mouse	Gyro	Unknown	27.1~27.3	x/x,z	1.1	Implicit control
ES120 screwdriver	Gyro	ST L3G4200D	19.8~20.0	y/y	2.6	Implicit control
B&D screwdriver	Gyro	IS ISZ650	30.3~30.6	z/z	0	Limited control
Dewalt screwdriver	Gyro	Unknown	Not found	none/y	N/A	Not affected
Oculus Rift	Gyro	BS BMI055	24.3~25.6	x/x,y,z	2.4	Implicit control
Oculus Touch	Gyro	IS MP651	27.1~27.4	x/x,y,z	1.6	Implicit control
Microsoft Hololens	Gyro	Unknown	27.0~27.4	x/x,y,z	0	Limited control
iPhone 5	Gyro	ST L3G4200D	19.9~20.1	x,y,z/x,y,z	5.8	Implicit control
iPhone 5S	Gyro	ST B329	19.4~19.6	x,y,z/x,y,z	5.6	Implicit control
iPhone 6S	Gyro	IS MP67B	27.2~27.6	x,y,z/x,y,z	0.8	Implicit control
iPhone 7	Gyro	IS 773C	27.1~27.6	x,y,z/x,y,z	2.0	Implicit control
Huawei Honor V8	Gyro	ST LSM6DS3	20.2~20.4	x,y,z/x,y,z	7.7	Implicit control
Google Pixel	Gyro	BS BMI160	23.1~23.3	x,y,z/x,y,z	0.4	Implicit control
Pro32 soldering iron	Acce	NX MMA8652FC	6.2~6.5	Unknown	1.1	DoS

† IS: InvenSense, ST:STMicroelectronics, BS: Bosch, NX: NXP Semiconductors.

Open-loop Control Systems

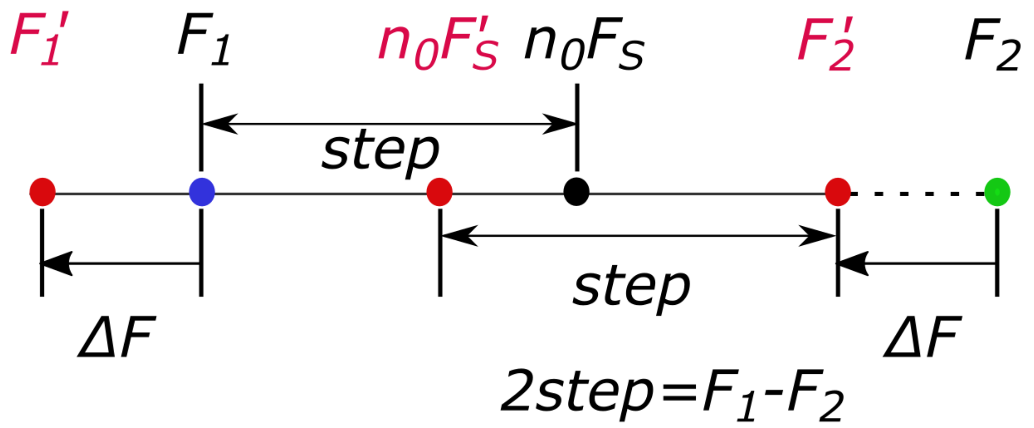
- **3D mouse**
  - Side-Swing: https://youtu.be/YoYpNeIJh5U
  - Switching: https://youtu.be/iWXTJ6We0UY
- **VR/AR device**
  - Side-Swing: https://youtu.be/KciiDeFdK9c
  - Switching: https://youtu.be/Jf9xHAW1PJY
  - Switching: https://youtu.be/MtXxcSzWcQA
- **Smartphone**
  - Side-Swing: https://youtu.be/t9rNJsDdGPg
  - Side-Swing: https://youtu.be/Wl6c_zBGlpU
  - Switching: https://youtu.be/psuOhyUvDQk
  - Switching: https://youtu.be/P4nLuTQZJ80
- **Motion-aware device (soldering iron)**
  - DoS: https://youtu.be/itgmOl21zoc

Conservative Side-Swing attacks on a screwdriver

- **Gyroscopic screwdriver**
  - Conservative Side-Swing: https://youtu.be/SCAYbyMIJAc

Automatic Switching Attack with Feedback

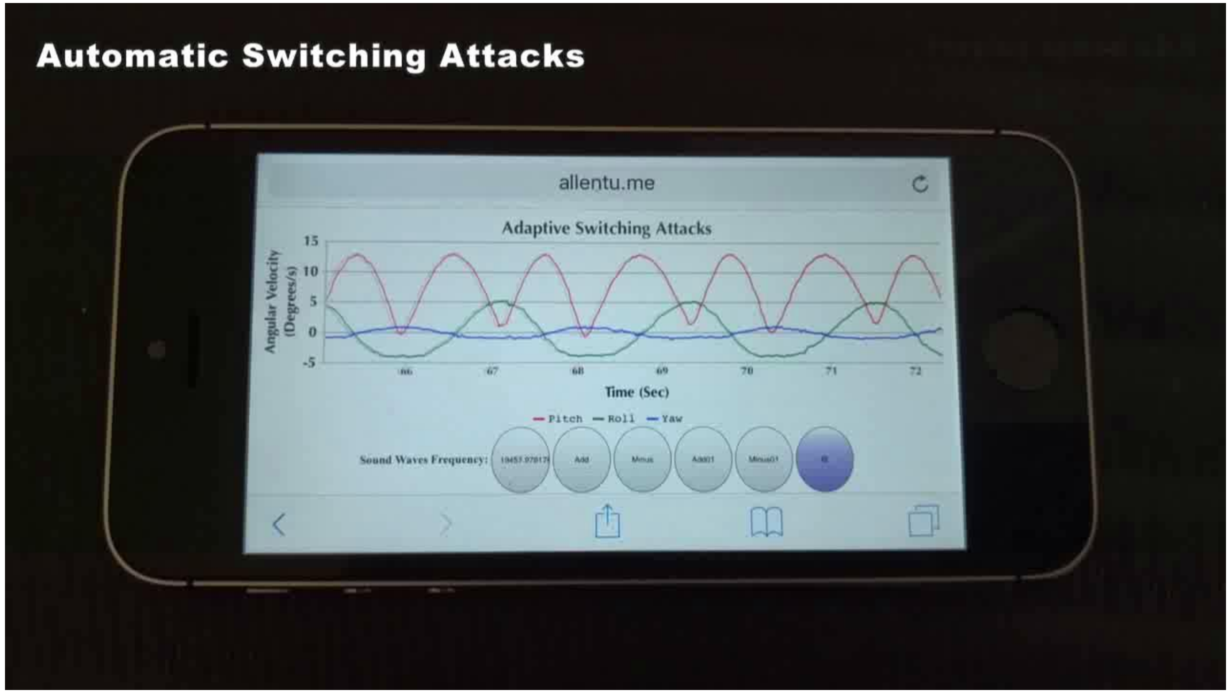
- Motivation:
  - Hand tuning is slow
  - Devices provide inertial sensor feedback
- Program modulates acoustic signals
  - More effective
  - Active adaptation



Adaptation Process

Implementations of Automatic Attacks

- Proof-of-concept implementations
  - **Android (Google Maps)**
    - https://youtu.be/dy6gm9ZLKuY
  - **IOS (VR game)**
    - https://youtu.be/kTQFi9CI8R8
  - **Web scripts (sample rate < 20 Hz)**
    - https://youtu.be/MkpW_j6gd8k
    - https://youtu.be/7yOSFTeF1so
    - **Resonant frequency scanner** https://youtu.be/vUDSvsfnJjg
  - **A moving phone**
    - https://youtu.be/1J1Q1jSzOD4
  - **Built-in speaker frequency < 24 kHz**

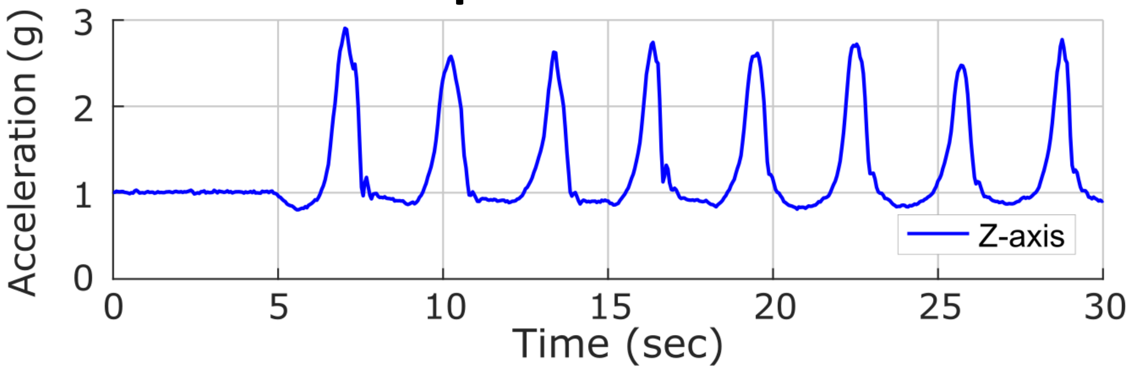


Rotating the orientation of Google Maps

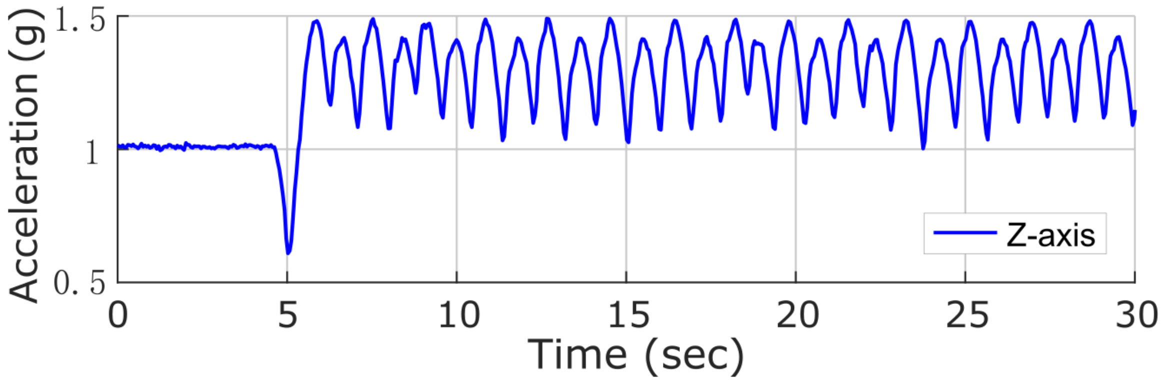
Shooting germs in VR games

Generalization: Using Non-resonant Frequencies

Accelerometer output:



Side-Swing attack (F=19.6 Hz)

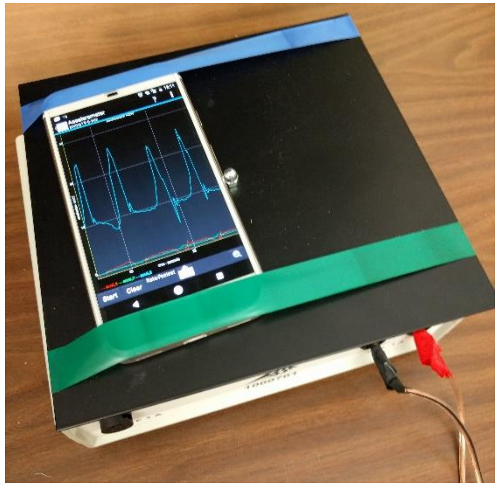


Switching attack (F1=19.4 Hz, F2=20.4 Hz)

- **Google Pixel smartphone on a vibration platform**
  - ***Vibration signals* with low frequency**
  - Sample rate of the ADC *Fs≈19.9*
- Accelerometer data shows:
  - **Launching to the sky**
  - **Accumulate a speed of over *70 m/s***

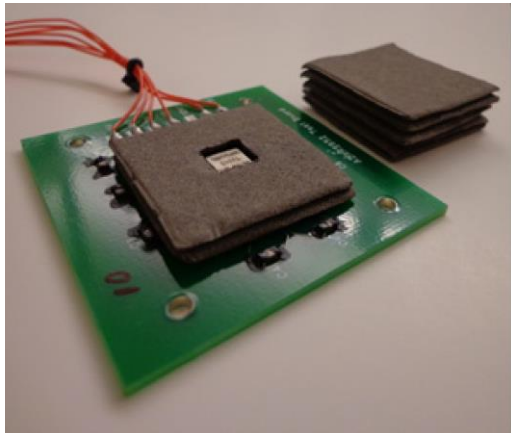
Sensor data shows

In reality

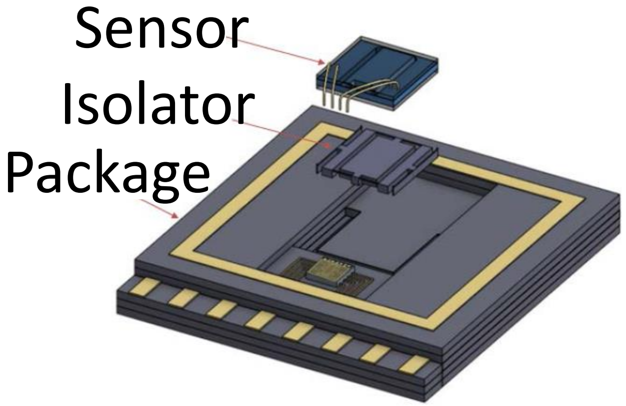


Possible Mitigation Methods

- Damping and isolation
  - Acoustic damping material
  - Isolating
  - Design suggestion
- Filtering and sampling
  - Low-pass filter [2]
  - Randomized and 180° out-of-phase sampling [2]
  - Dynamic sample rate *Fs*
- Redundancy-based approaches



Microfibrous cloth[3]



Micro-isolator[4]

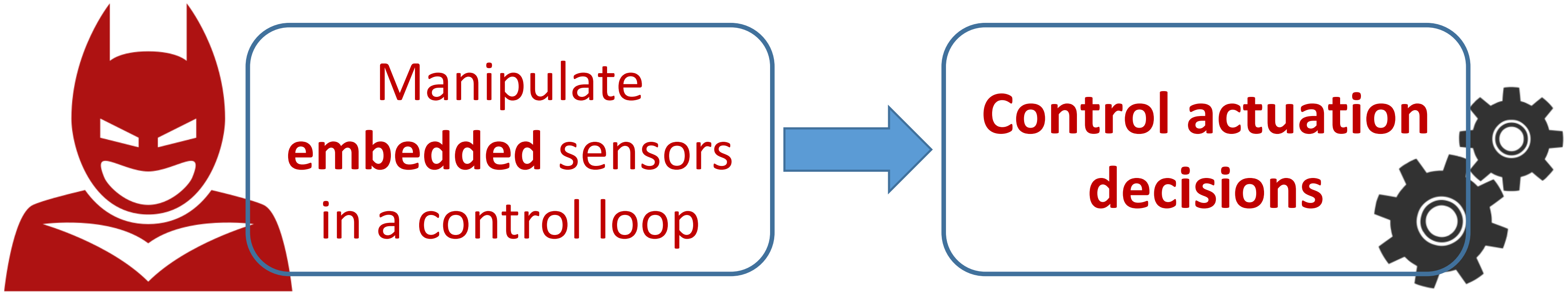
Discussion

- **Attack experiment with a drone**
- **Sound source**
  - Professional acoustic devices
  - Speaker/Transducer arrays
    - *N* coherent sound sources (Ex: *N=8*)
    - Possible sound level increase: *20log10(N) = 18 dB*

Trying to make the drone tilt to the left twice and then to the right twice (Side-Swing)

Conclusion

- We explored non-invasive attacks on embedded inertial sensors (***black-box*** approach)
- In attacks on real devices, realistic factors need be considered
  - In undersampling, sample rate drifts can be amplified
- Possible to implicitly control different kinds of systems by acoustic injections on inertial sensors



References

[1] Son et al. "Rocking drones with intentional sound noise on gyroscopic sensors." *In Proc. of USENIX Security symposium,* 2015.

[2] Trippel et al. "WALNUT: Waging doubt on the integrity of MEMS accelerometers with acoustic injection attacks." In Proc. Of *IEEE European Symposium on Security and Privacy*, 2017.

[3] Soobramaney et al. "Mitigation of the Effects of High Levels of High-Frequency Noise on MEMS Gyroscopes Using Microfibrous Cloth." In *ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2015.

[4] Kranz et al. "Environmentally Isolating Packaging for MEMS Sensors." In *International Symposium on Microelectronics*, 2017. International Microelectronics Assembly and Packaging Society.

Questions & Comments

Thank You !

- Email: yazhou.tu1@louisiana.edu

- Attack demos are available in our YouTube Channel!

https://www.youtube.com/channel/UCGMX3ZbElV7BZYIX7RtF5tg

- Our earlier demos can be found at:

https://www.youtube.com/channel/UCeV47TrMGvnrcXgZesJYHtA