USENIX Security Symposium 2015

Rocking Drones with Intentional Sound Noise on Gyroscopic Sensors

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System Security Lab.

KAIST

Drones (Multi-coptors)

- ❖ Distribution delivery
- ❖ Search and rescue
- ❖ Aerial photography
- ❖ Private hobby

Drone, A New Threat

- Air terrorism using a weaponized drone

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The Switch

Watch the Pirate Party fly a drone in front of Germany's chancellor Sep. 2013

Attack Vectors of Drone

Drone

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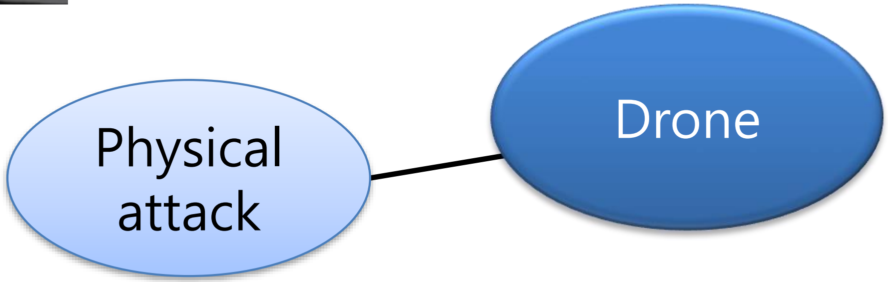

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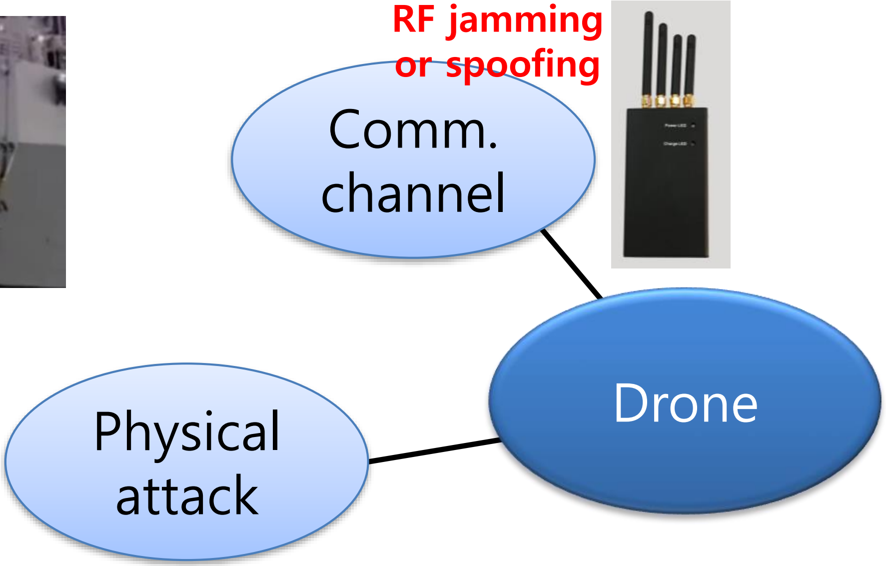

Attack Vectors of Drone

Physical attack

RF jamming or spoofing

Comm. channel

Drone

Software hacking

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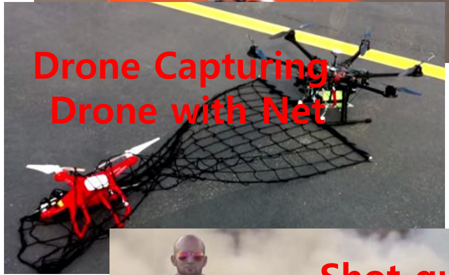

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- Comm. channel
- Software hacking
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- Sensing channel

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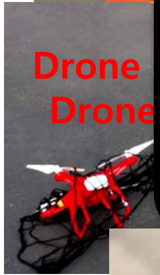


RF jamming or spoofing

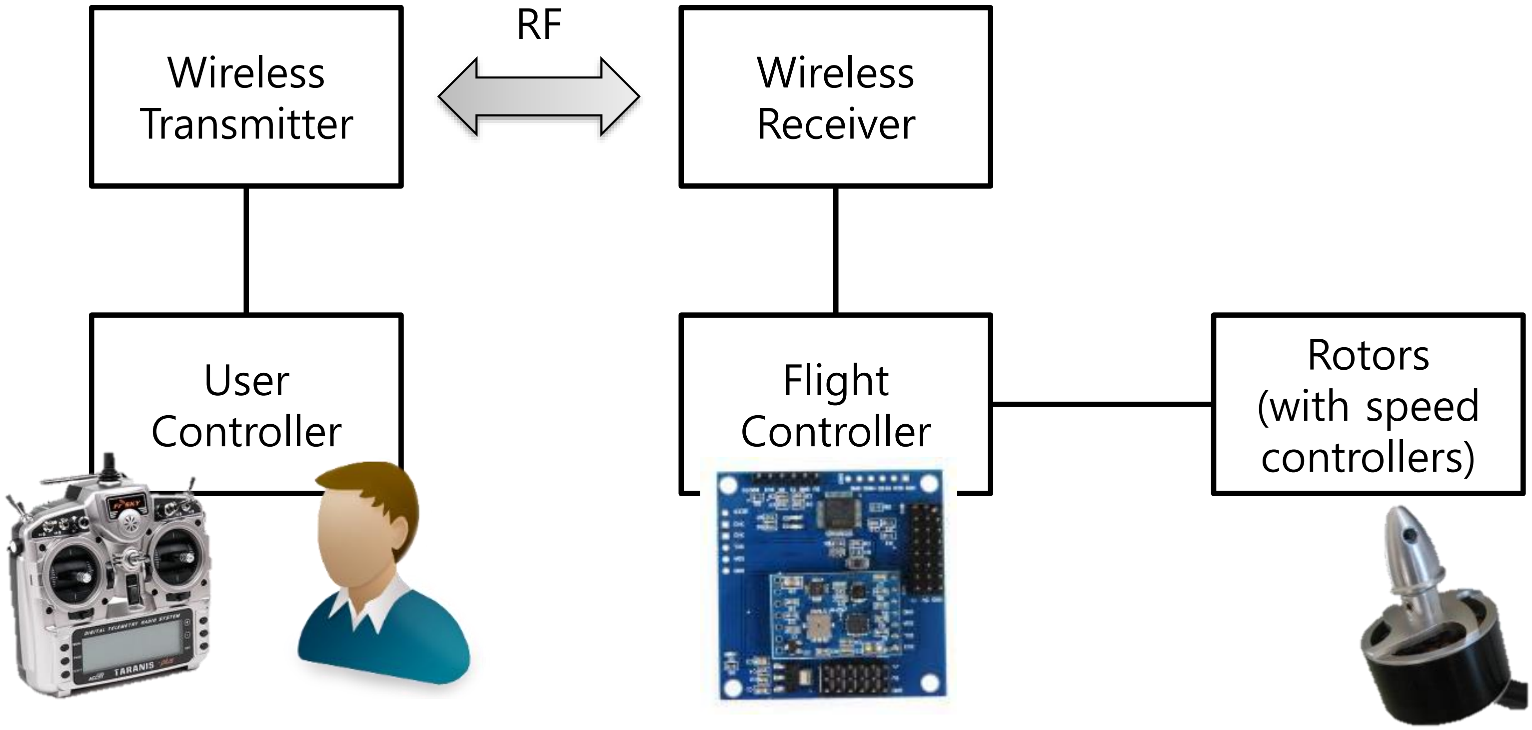
Comm. channel

Software hacking

How secure is drone against interference on sensing channel?

Sensing channel

Drone System



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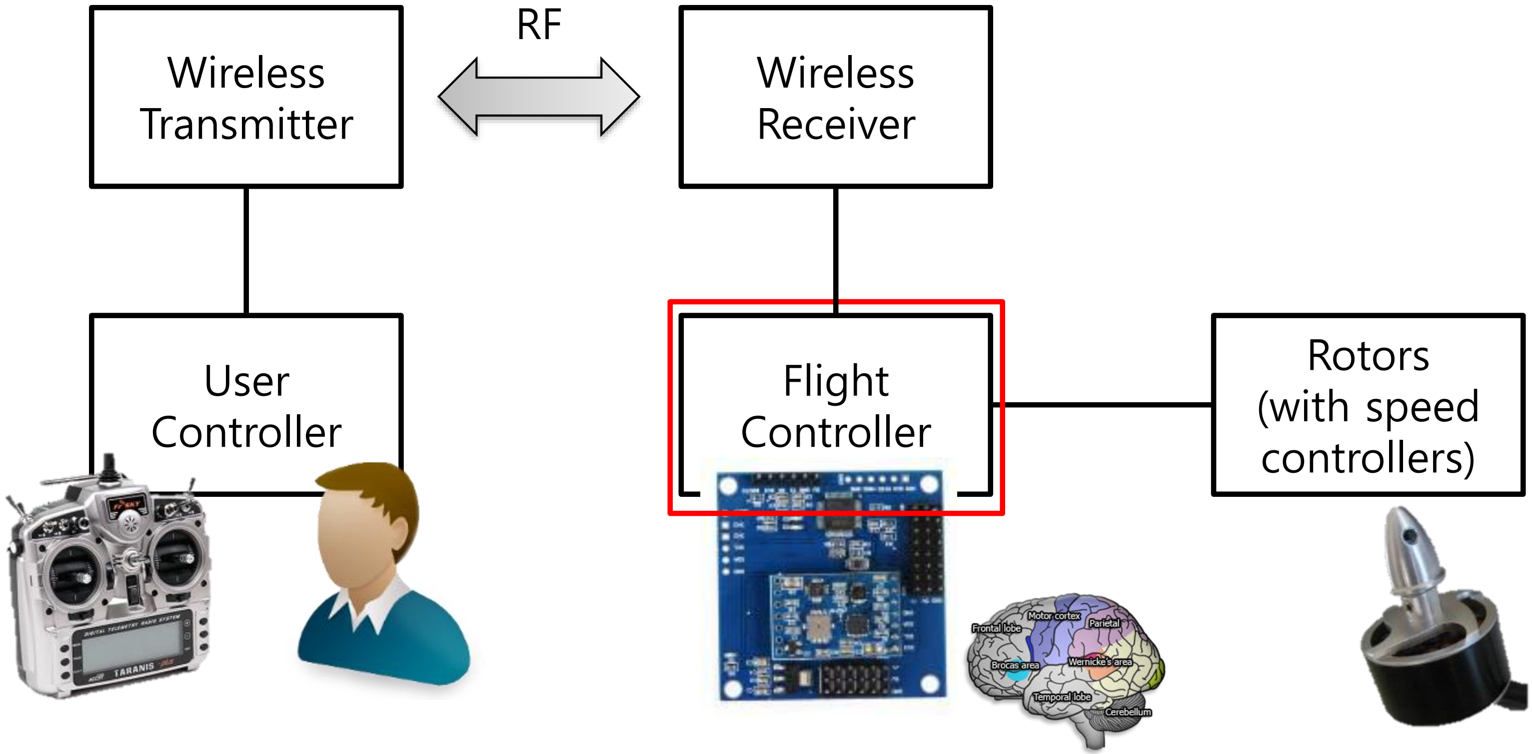

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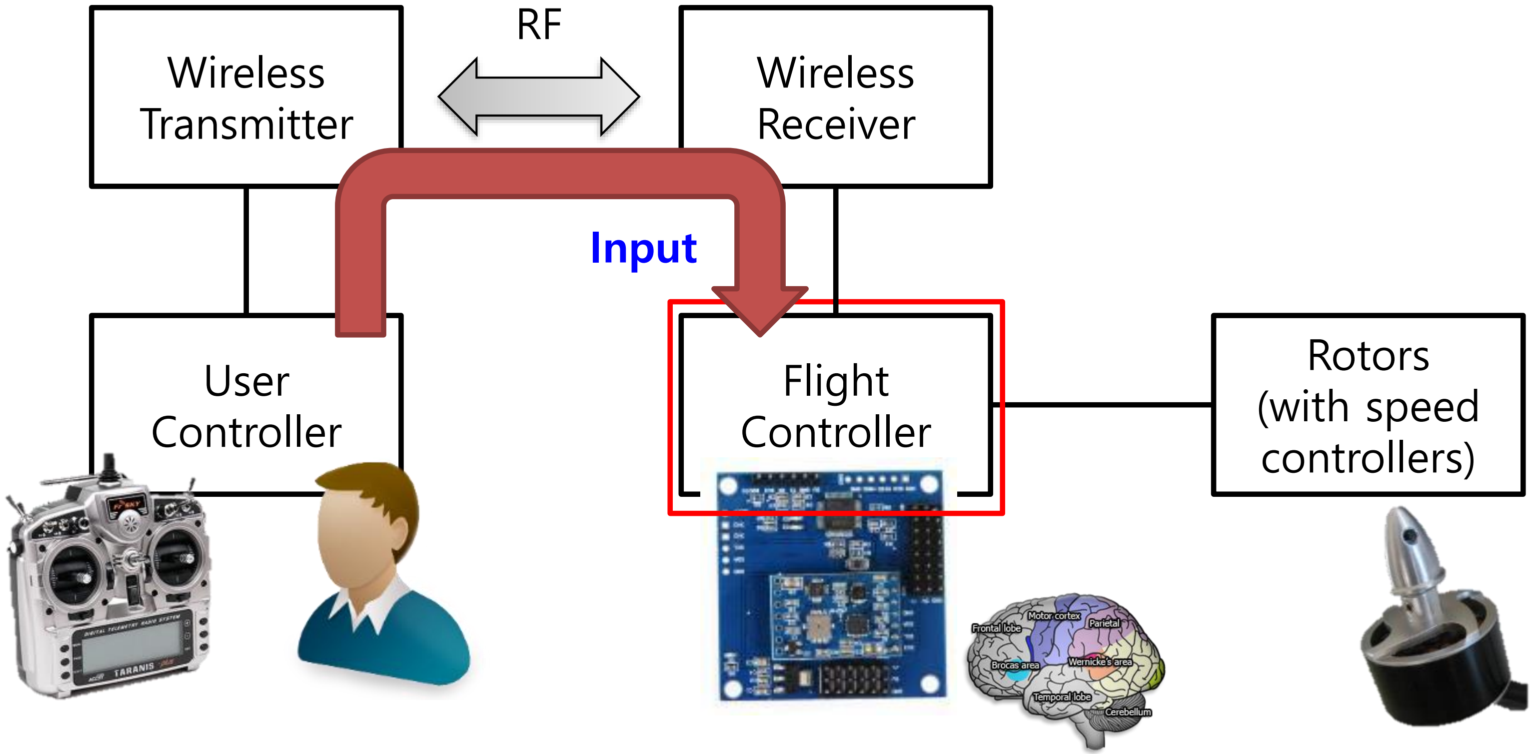

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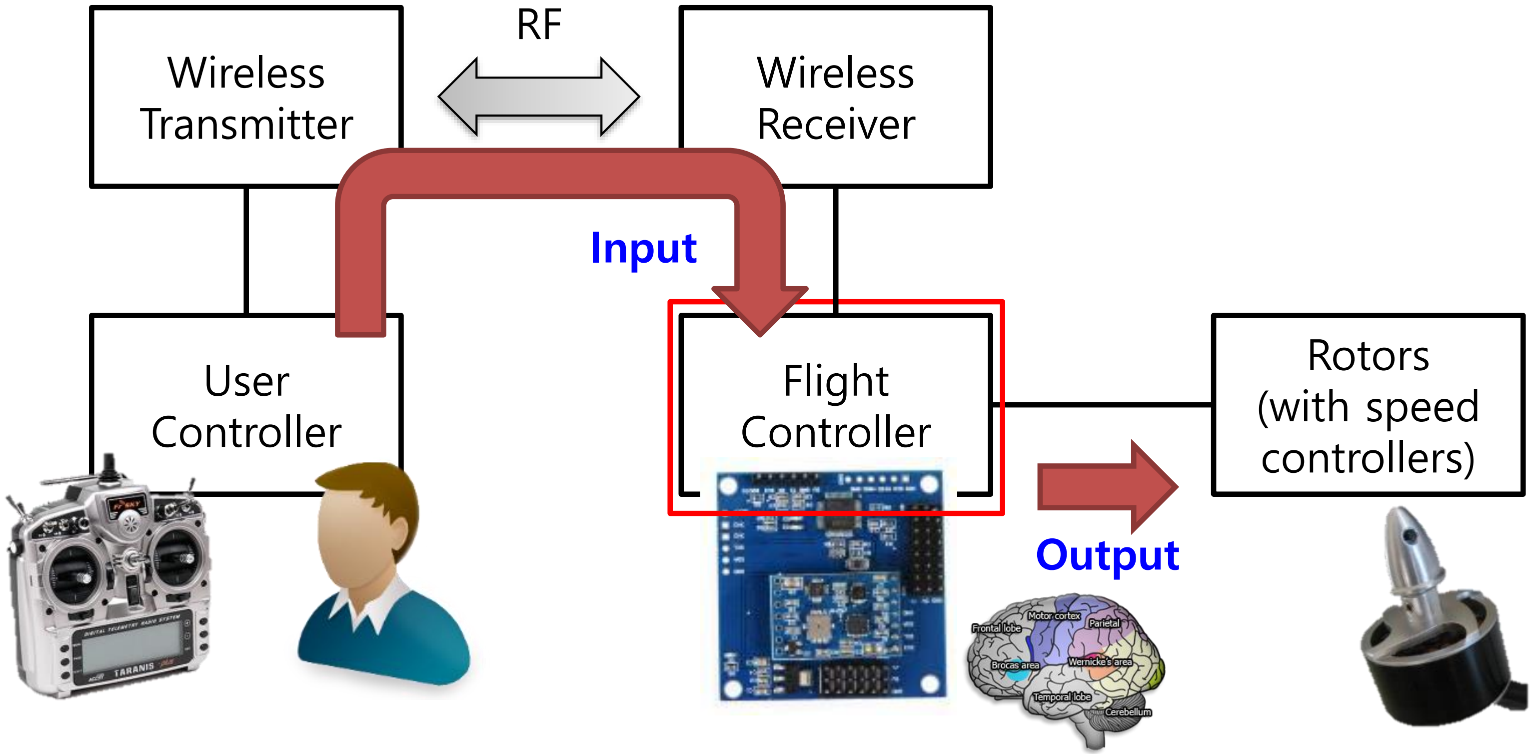
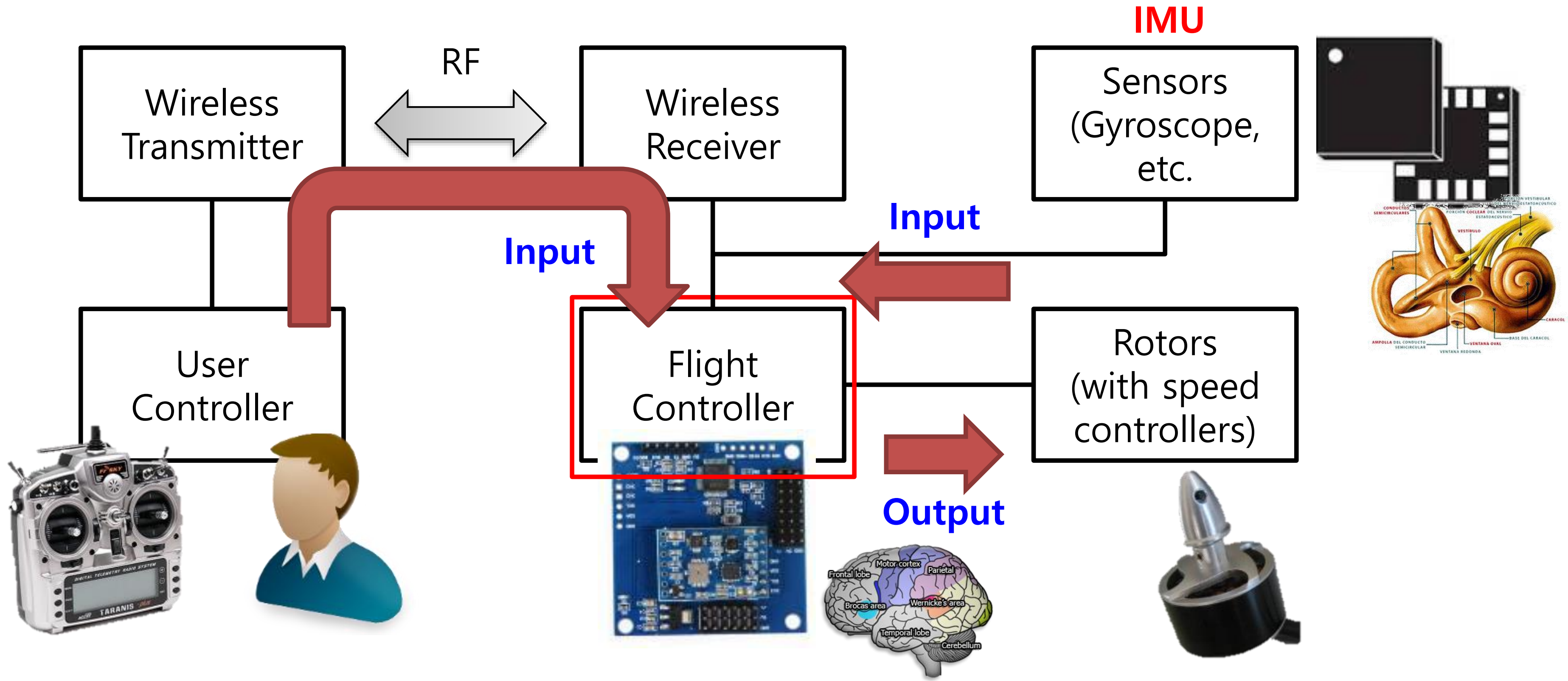


Drone System

* IMU: Inertial Measurement Unit



Gyroscope on Drone

* MEMS: Micro-Electro-Mechanical Systems

- Inertial Measurement Unit (IMU)
  - A device to measure velocity, orientation, or rotation
  - Using a combination of **MEMS gyroscopes** and accelerometers

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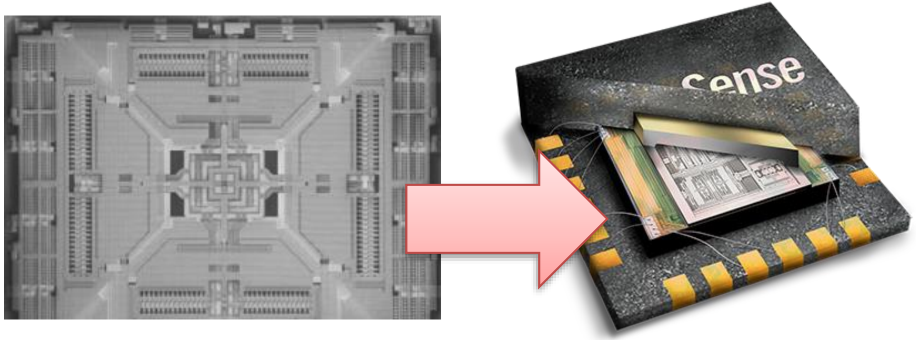

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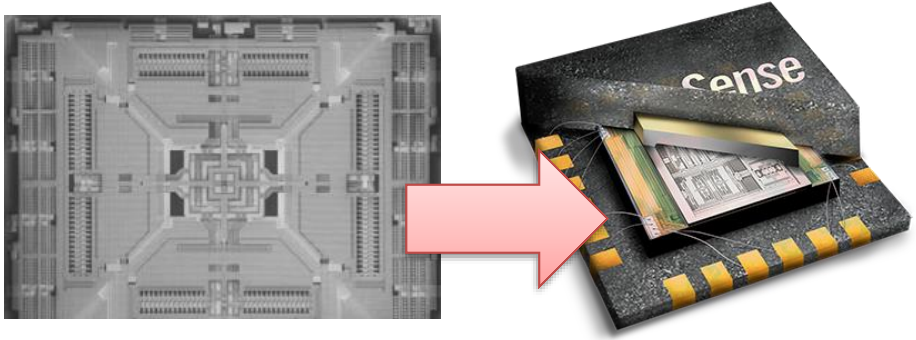
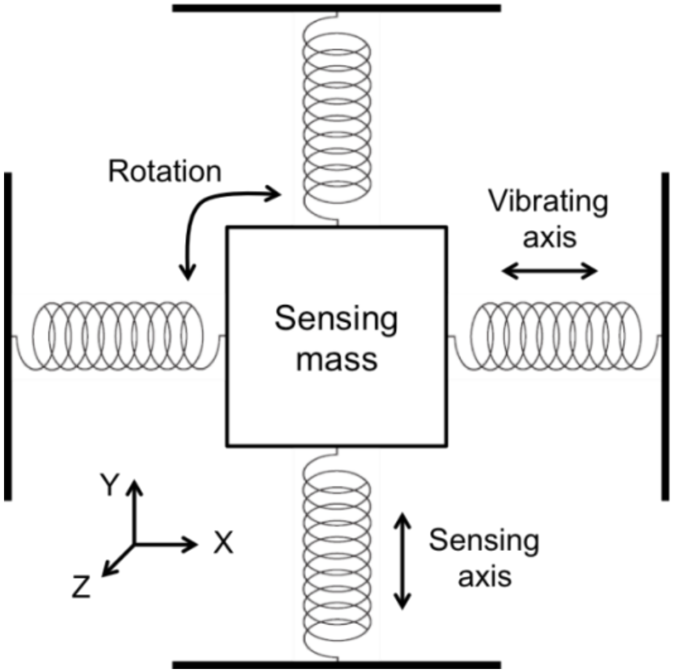


<Conceptual structure of MEMS gyro.>



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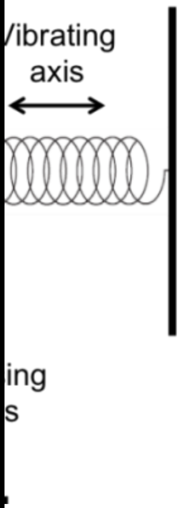

(https://www.youtube.com/watch?v=joS6kfjuKQo, https://www.youtube.com/watch?t=45&v=sH7XSX10QkM)

Resonance in MEMS Gyroscope

- ❖ Mechanical resonance by sound noise
  - – Known fact in the MEMS community
  - – Degrades MEMS Gyro's accuracy
  - – With (resonant) frequencies of sound

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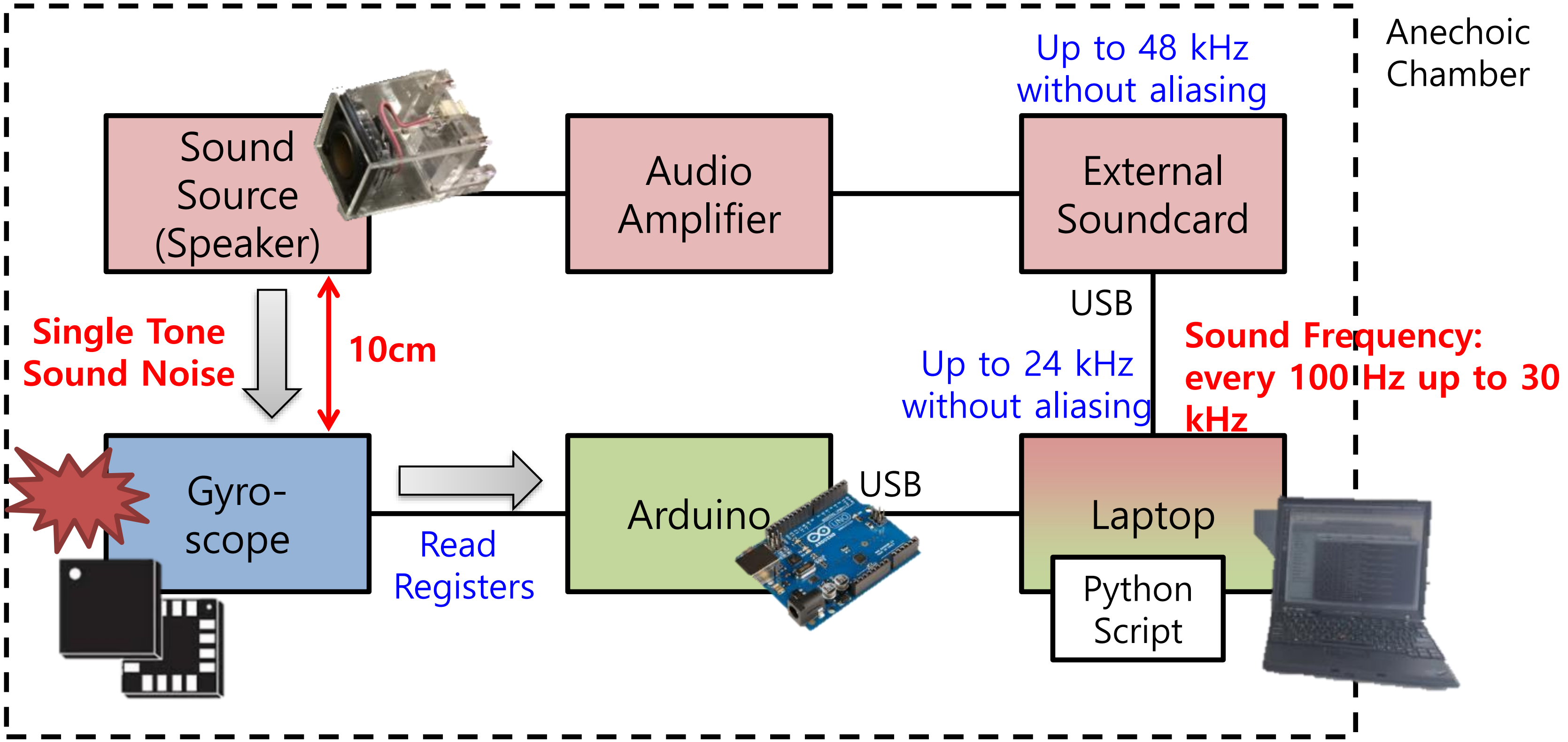
L3GD20

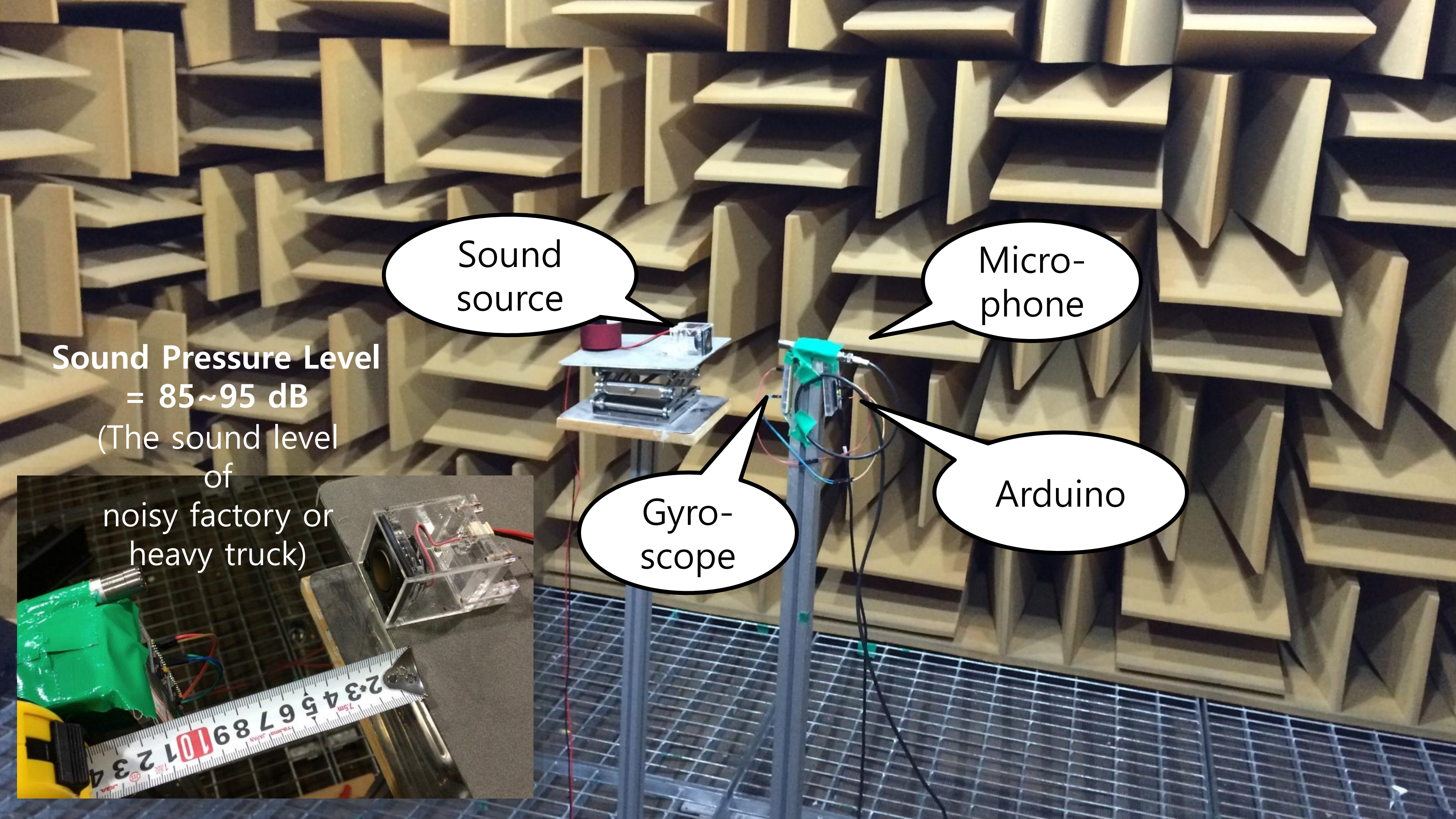
Features

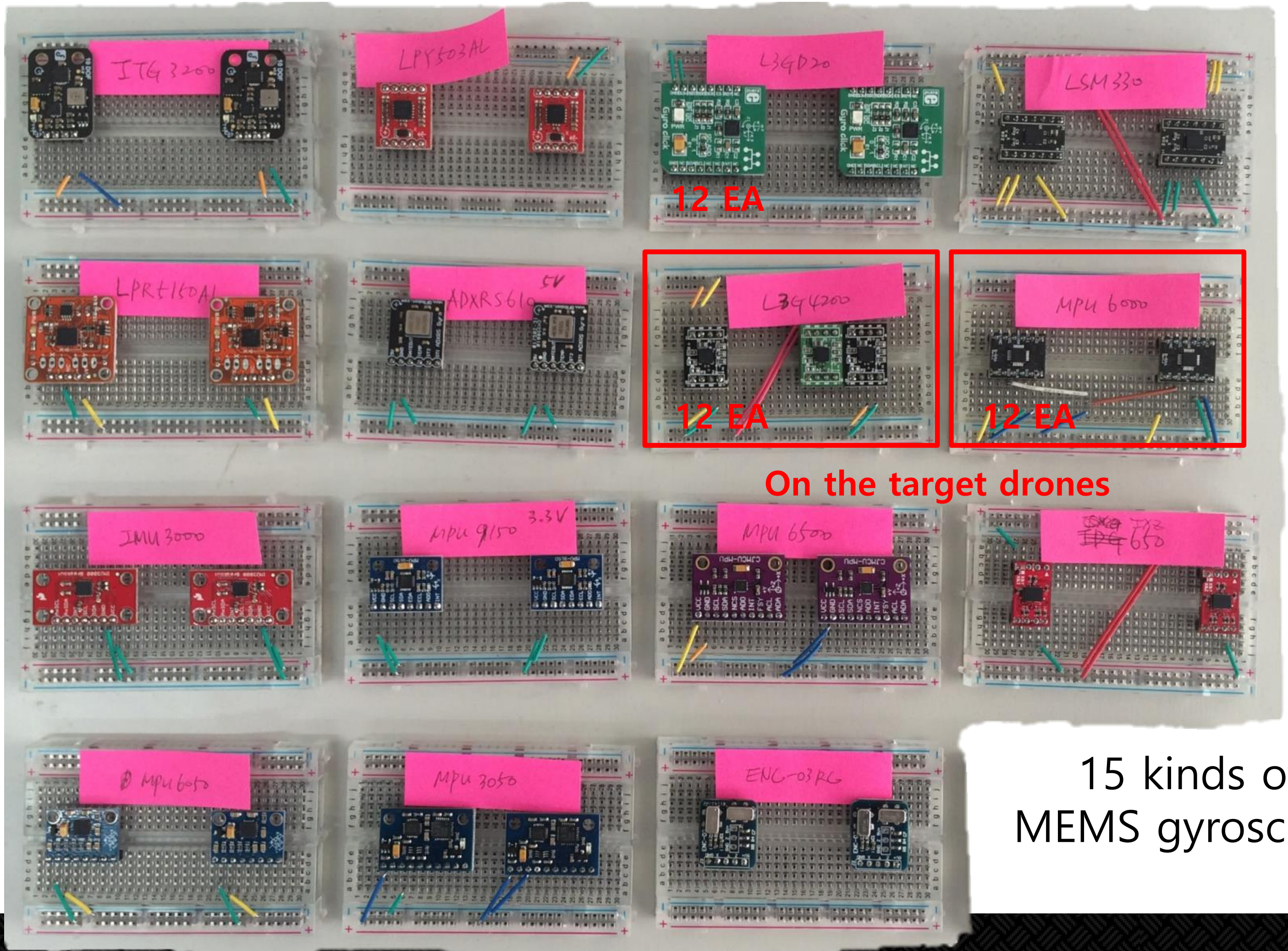
- Three selectable full scales (±250/500/2000 dps)
- 20+ kHz resonant frequency over the audio bandwidth

MEMS Gyro. with a high resonant frequency
to reduce the sound noise effect (above 20kHz)

Experiment Setup




Sound source
Micro-phone
Sound Pressure Level
= 85~95 dB
(The sound level of noisy factory or heavy truck)
Gyro-scope
Arduino



15 kinds of
MEMS gyroscopes

Experimental Results (1/3)

- Found the resonant frequencies of **7 MEMS gyroscopes**
- Not found for 8 MEMS gyroscopes

Sensor	Vender	Supporting Axis	Resonant freq. in the datasheet (axis)	Resonant freq. in our experiment (axis)
L3G4200D	STMicro.	X, Y, Z	No detailed information	**7,900 ~ 8,300 Hz (X, Y, Z)**
L3GD20	STMicro.	X, Y, Z		19,700 ~ 20,400Hz (X, Y, Z)
LSM330	STMicro.	X, Y, Z		19,900 ~ 20,000 Hz (X, Y, Z)
MPU6000	InvenSense	X, Y, Z	30 ~ 36 kHz (X) 27 ~ 33 kHz (Y) 24 ~ 30 kHz (Z)	**26,200 ~ 27,400 Hz (Z)**
MPU6050	InvenSense	X, Y, Z		25,800 ~ 27,700 Hz (Z)
MPU9150	InvenSense	X, Y, Z		27,400 ~ 28,600 Hz (Z)
MPU6500	InvenSense	X, Y, Z	25 ~ 29 kHz (X, Y, Z)	26,500 ~ 27,900 Hz (X, Y, Z)

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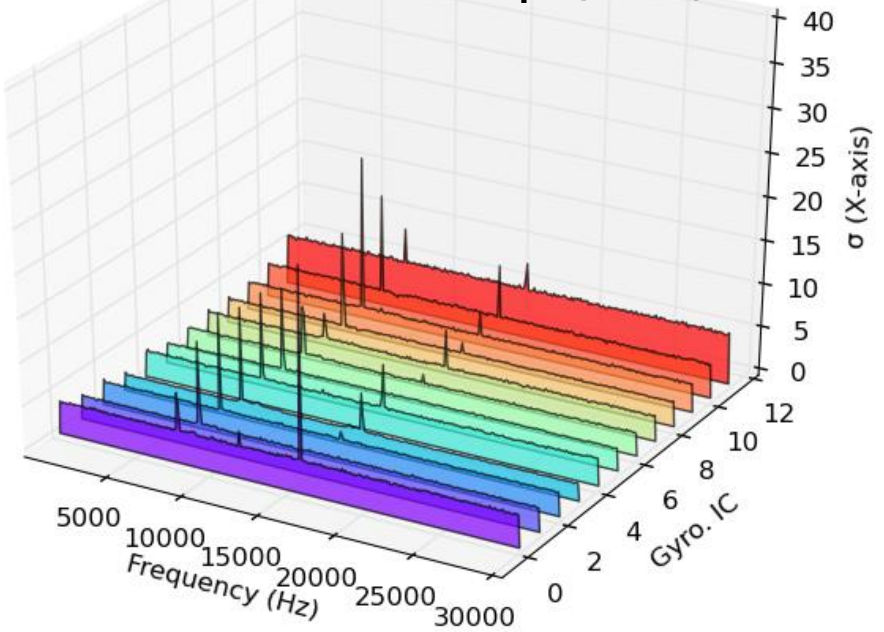
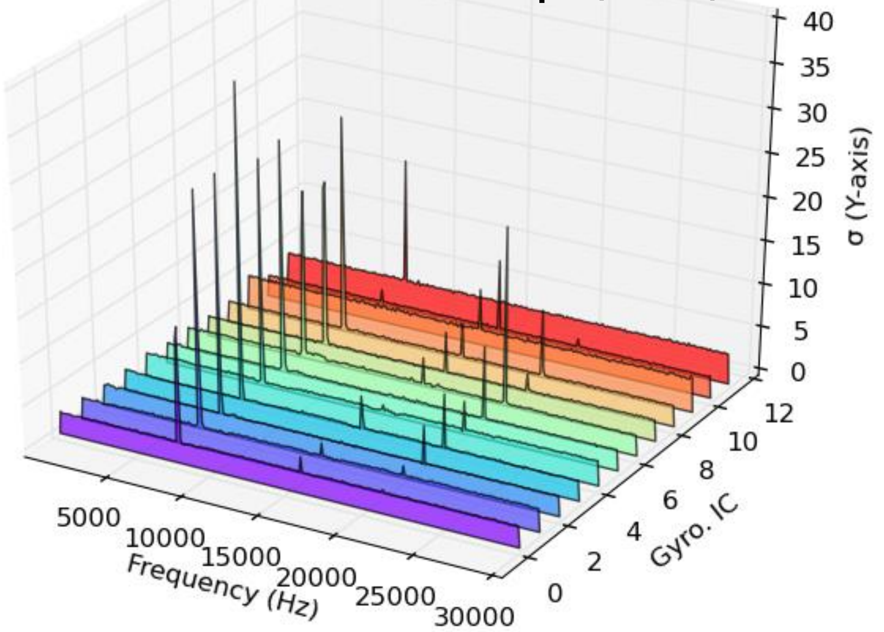
Experimental Results (2/3)

❖ Unexpected output by sound noise (for L3G4200D)

Standard deviation of raw data samples for 12 L3G4200D chips (X-axis)



Standard deviation of raw data samples for 12 L3G4200D chips (Y-axis)



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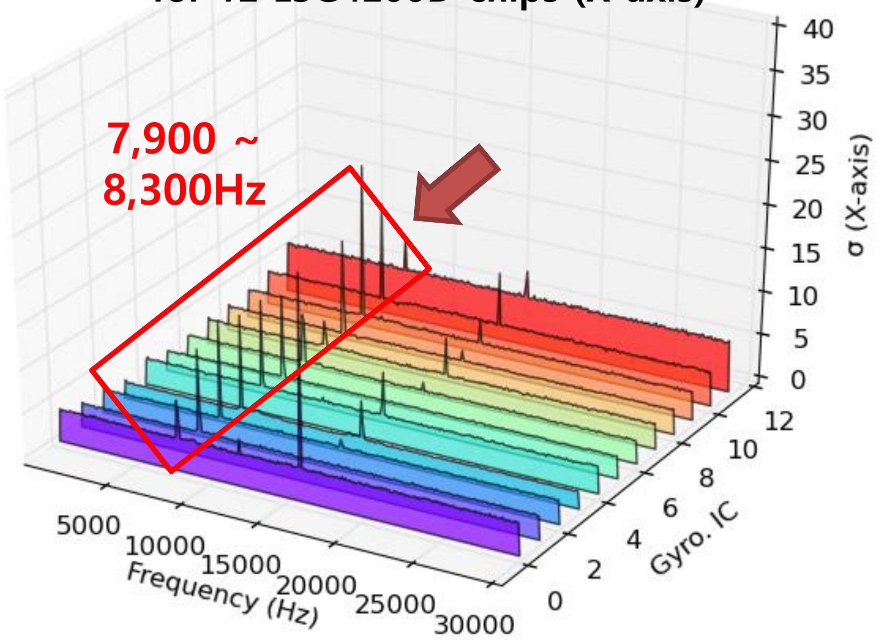

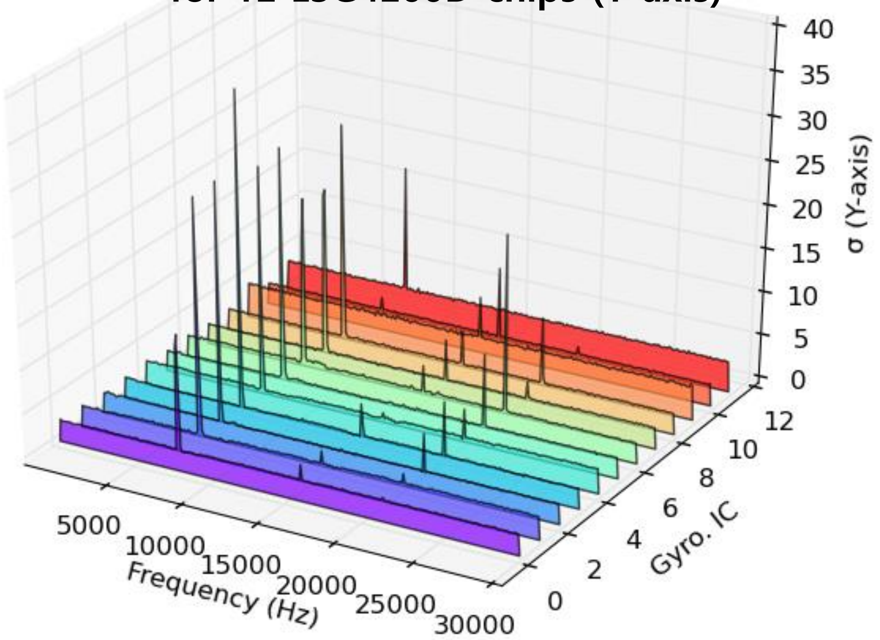

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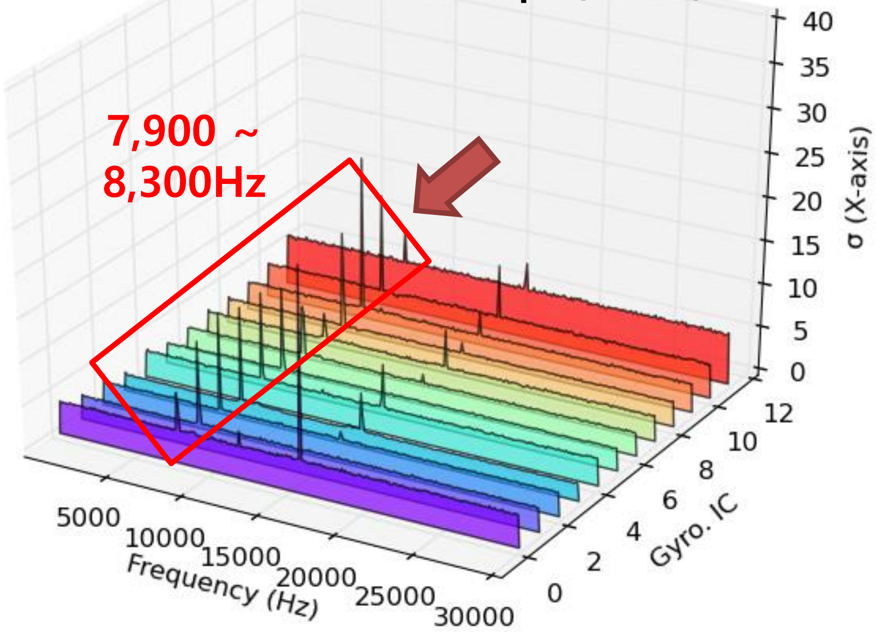

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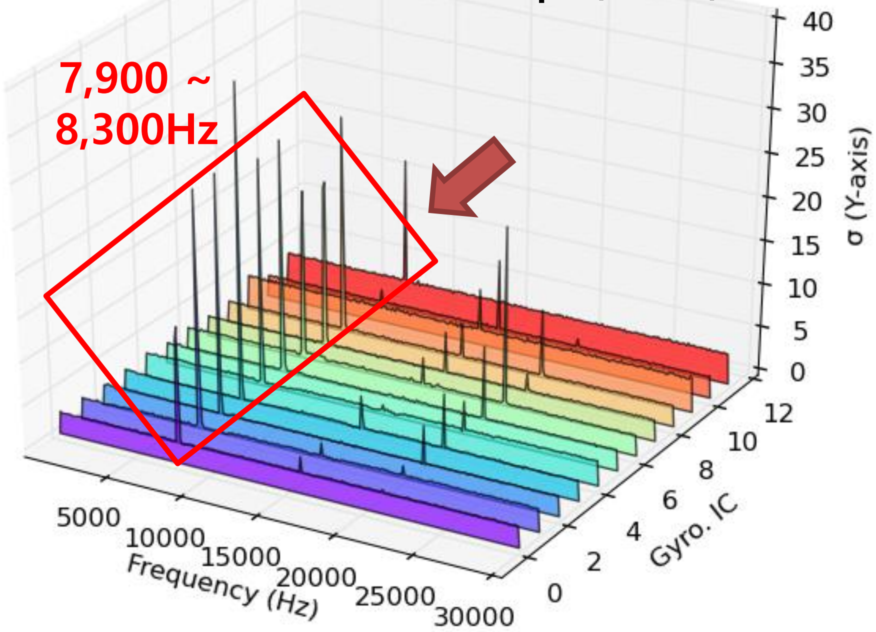

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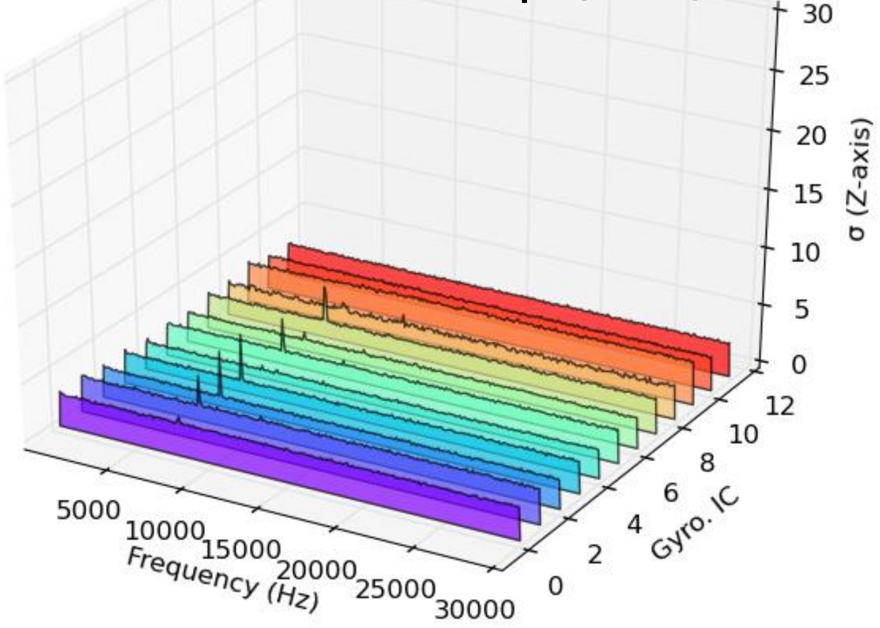
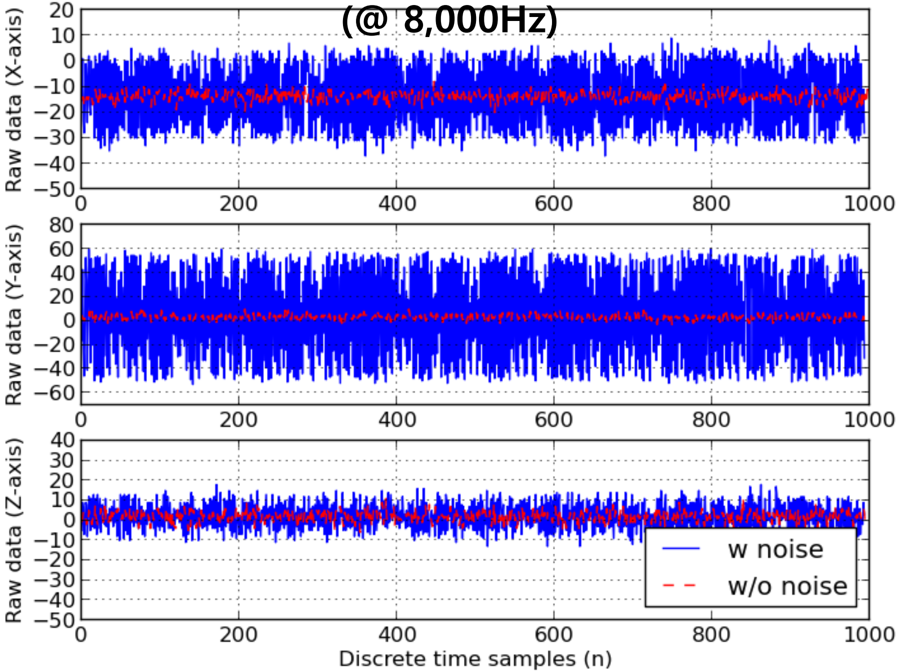


Raw data samples of one L3G4200D chip (@ 8,000Hz)



SysSec
System Security Lab

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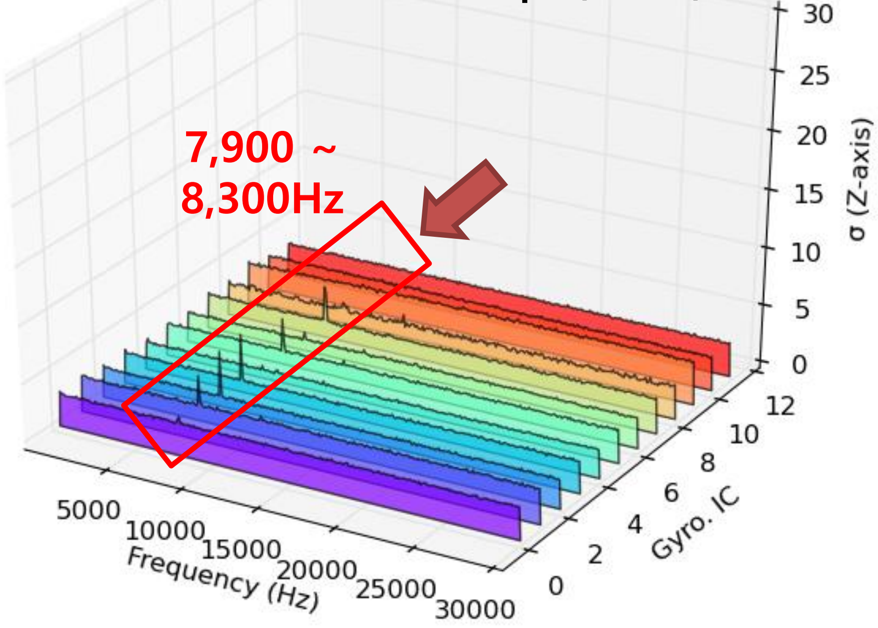

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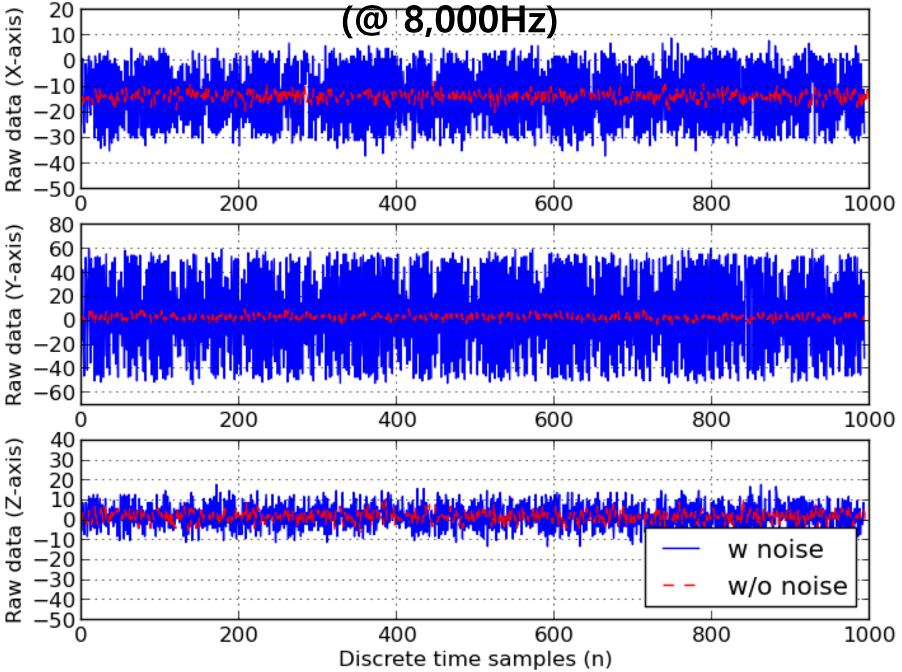

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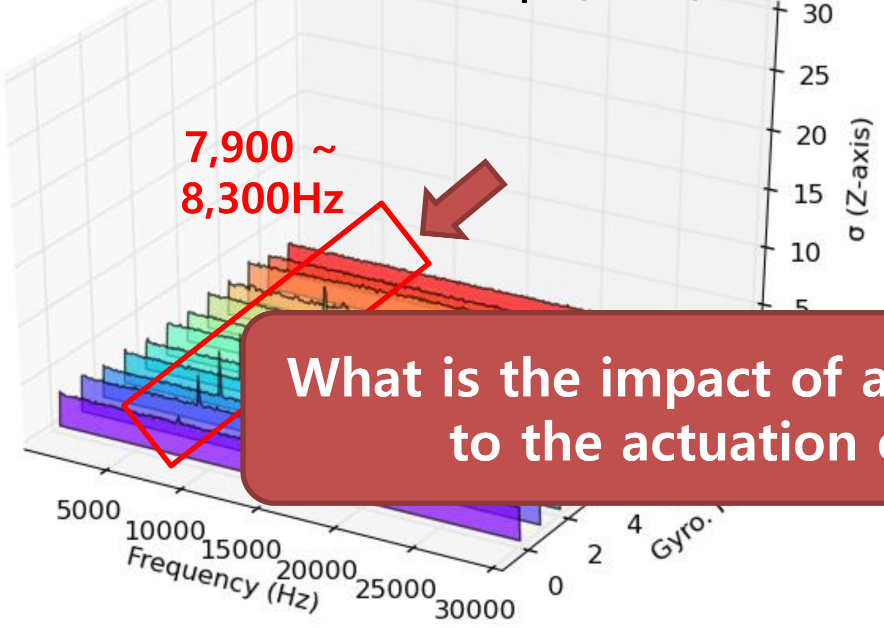

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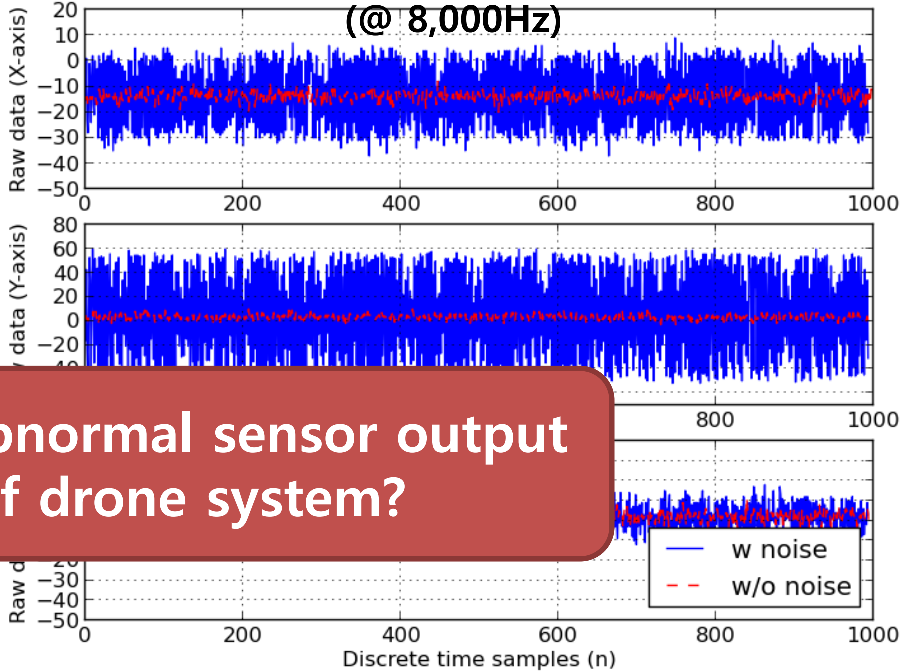

What is the impact of abnormal sensor output to the actuation of drone system?

Software Analysis

- Two open-source firmware programs
  - Multiwii project
  - ArduPilot project

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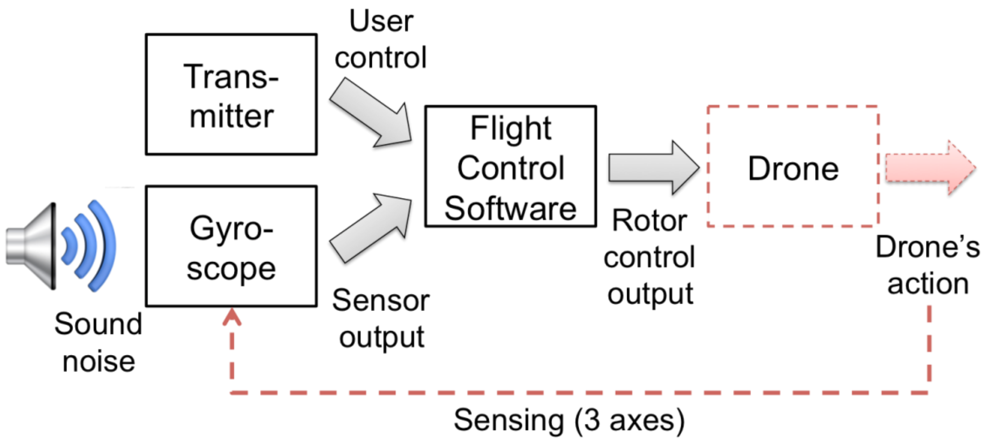

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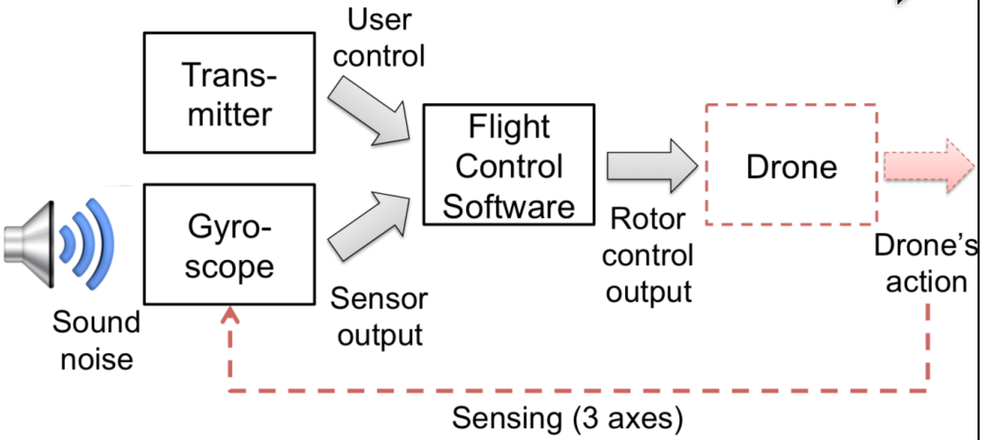

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$delta = gyro[axis] - gyro_{last}[axis];$

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for *rotor* **do**

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limit $rotorCtrl[rotor]$ within the pre-defined MIN (1,150) and MAX (1,850) values;

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actuate rotors;

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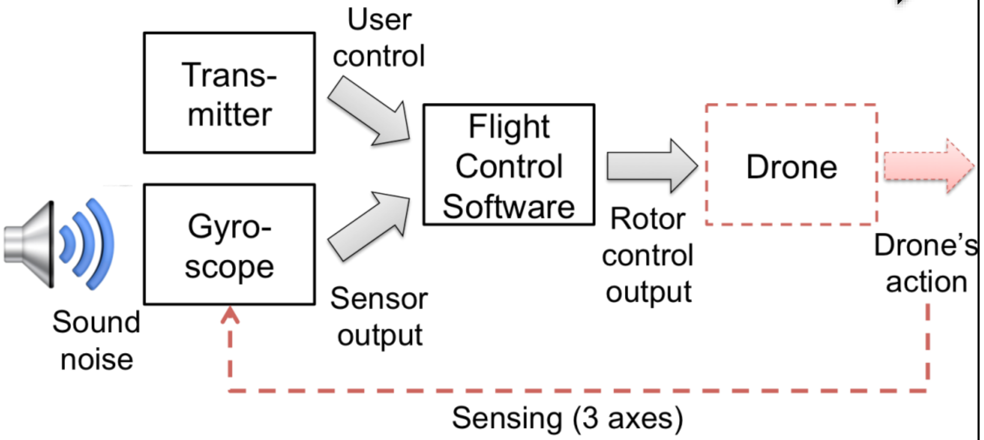

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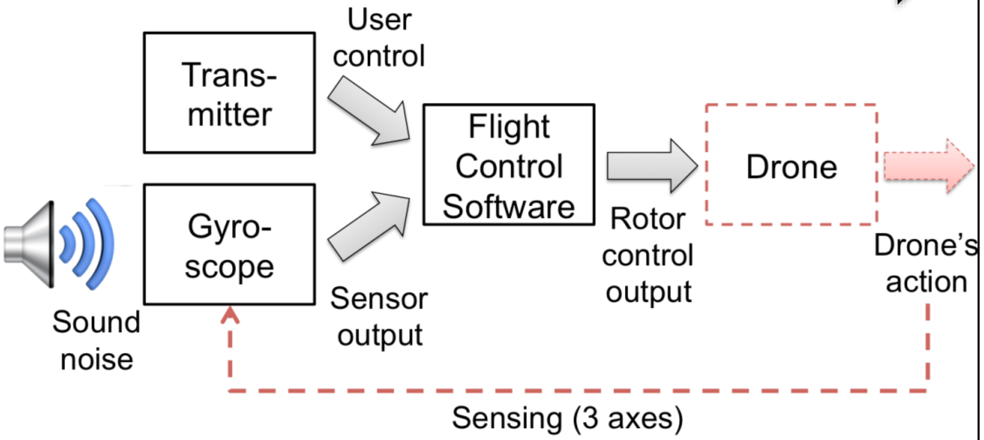

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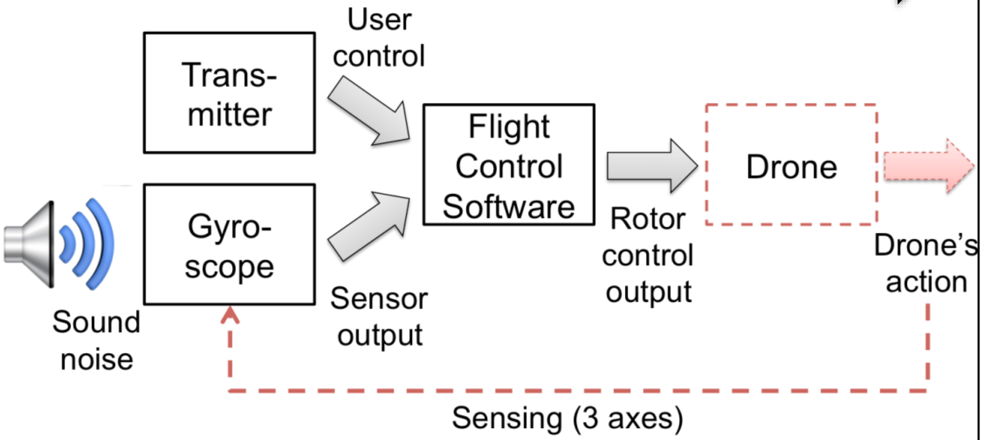

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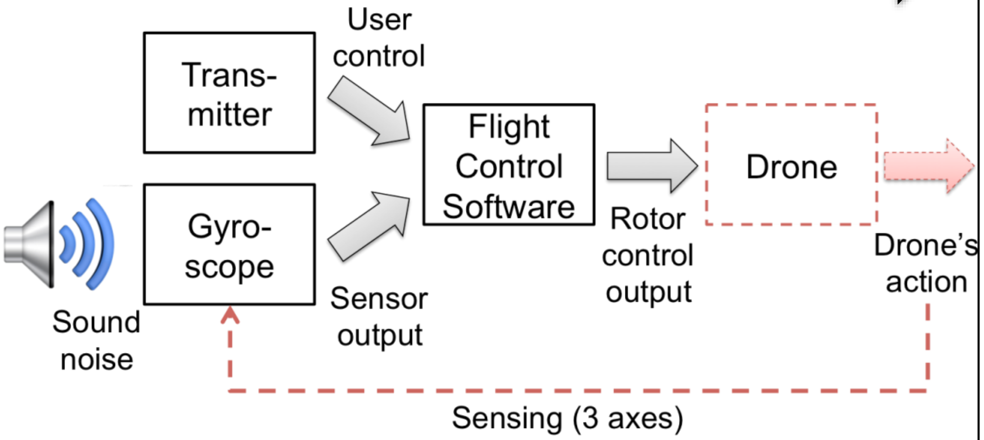

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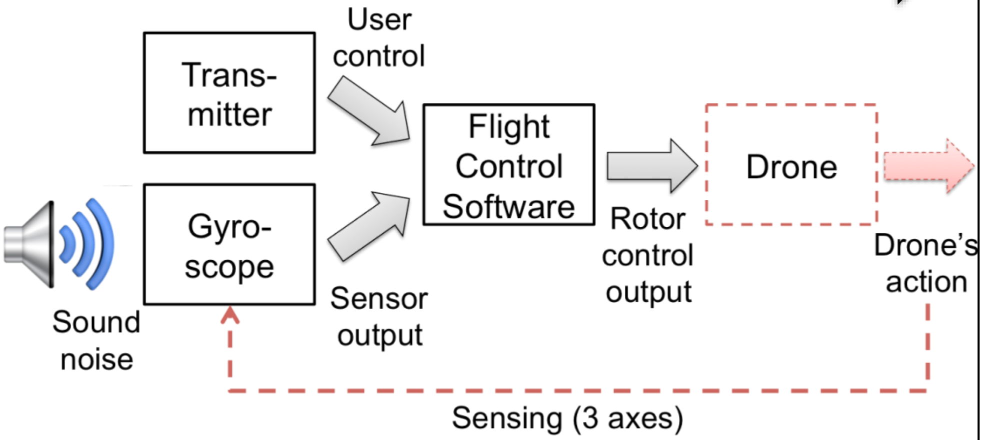

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for *rotor* **do**
- **for** *axis* **do**
  - $rotorCtrl[rotor] = txCtrl[throttle] + PIDCtrl[axis]$;
- **end**
- limit $rotorCtrl[rotor]$ within the pre-defined MIN (1,150) and MAX (1,850) values;

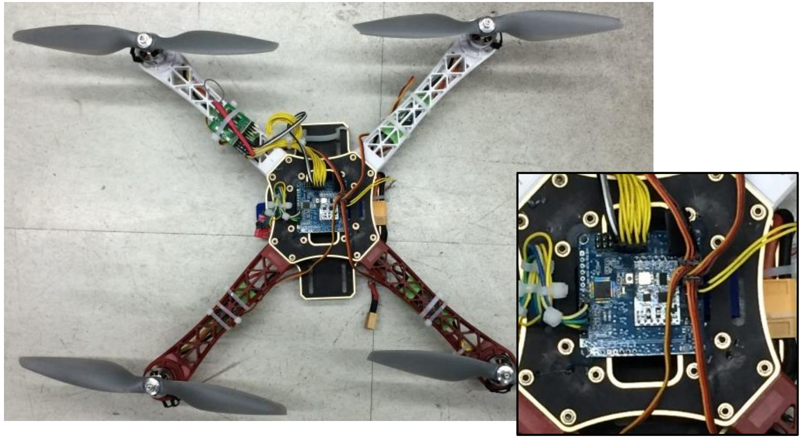
end

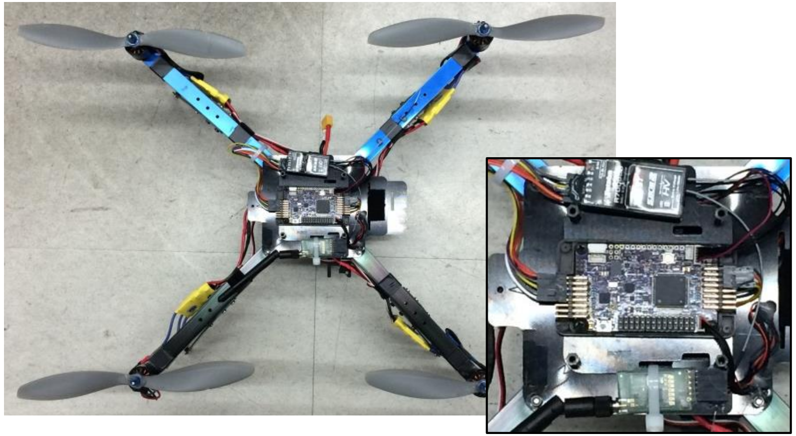
actuate rotors;

Target Drones

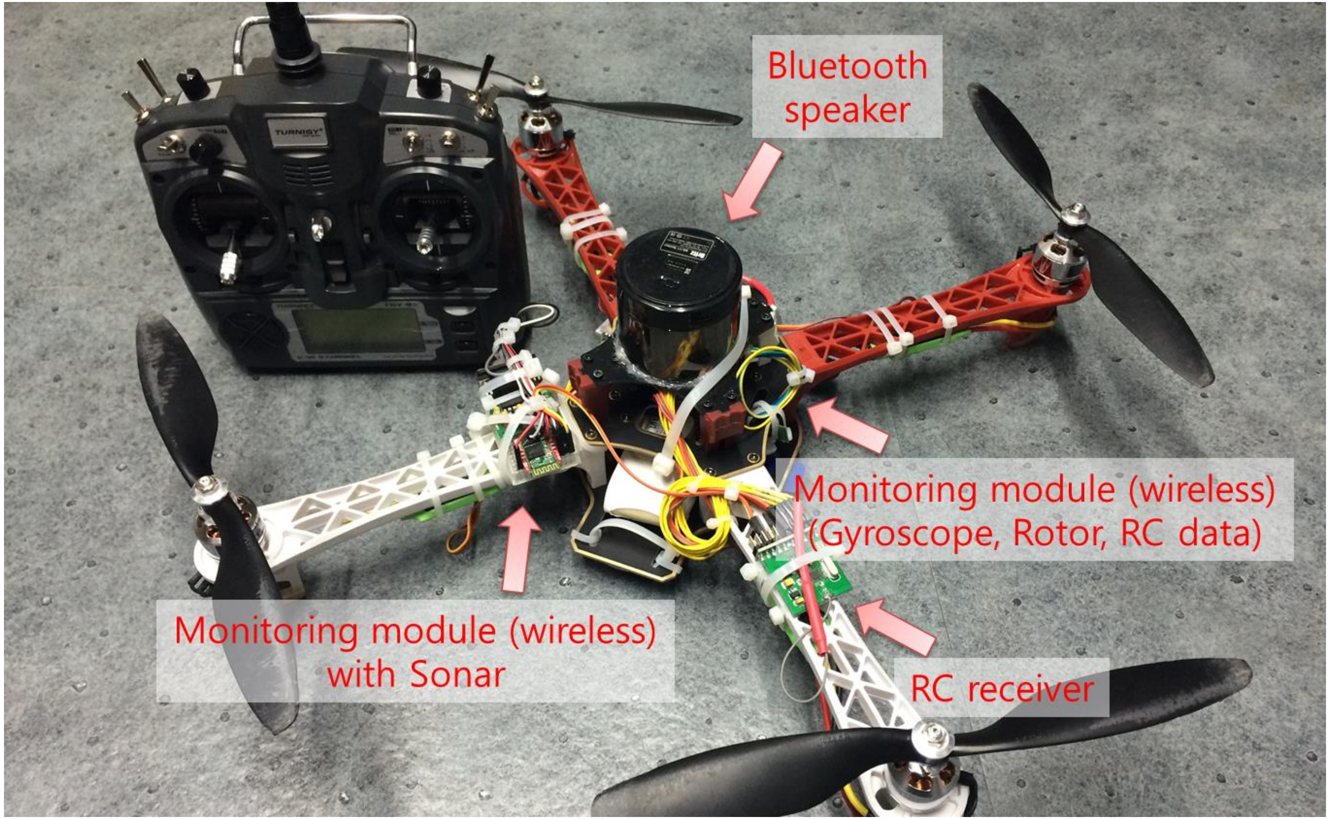
- Target drone A (DIY drone)
  - Gyroscope: L3G4200D
  - Resonant freq.: 8,200 Hz (Audible sound range)
  - Firmware: Multiwii

- Target drone B (DIY drone)
  - Gyroscope: MPU6000
  - Resonant freq.: 26,200 Hz (Ultra sound range)
  - Firmware: ArduPilot

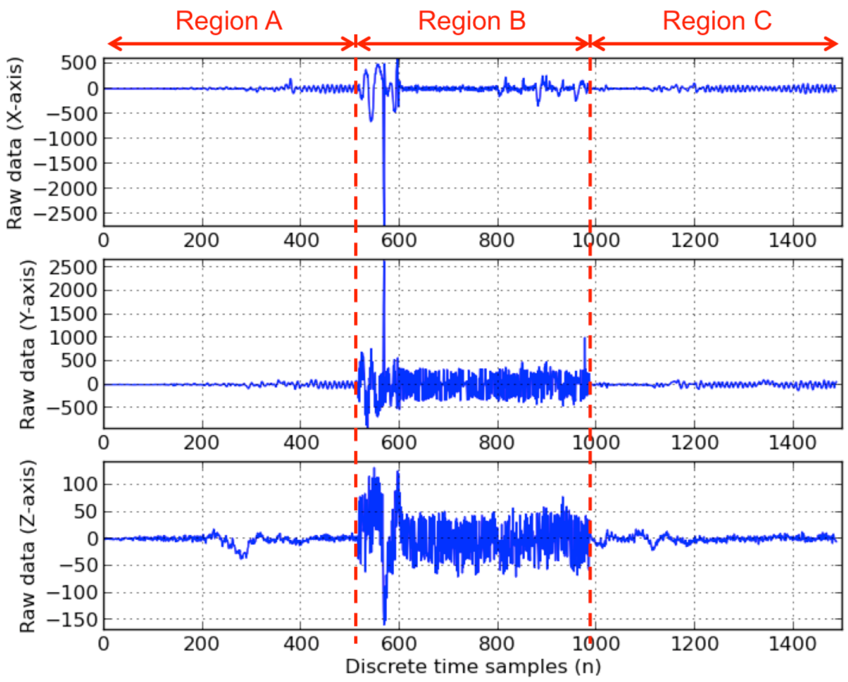




Attack DEMO


Bluetooth speaker
Monitoring module (wireless) (Gyroscope, Rotor, RC data)
Monitoring module (wireless) with Sonar
RC receiver

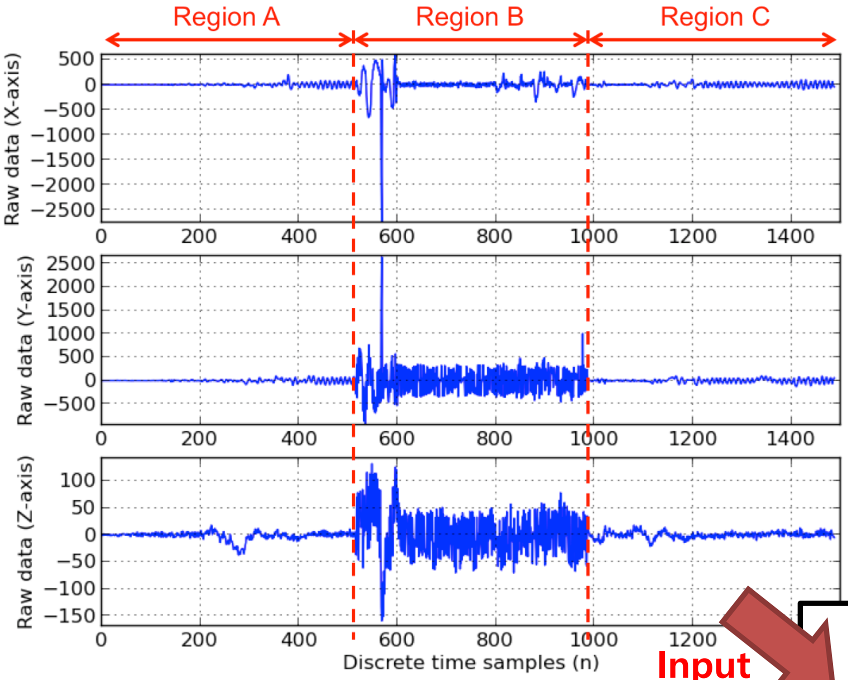
Attack DEMO (Target drone A)



Raw data samples of the gyroscope

SysSec System Security Lab

Attack DEMO (Target drone A)

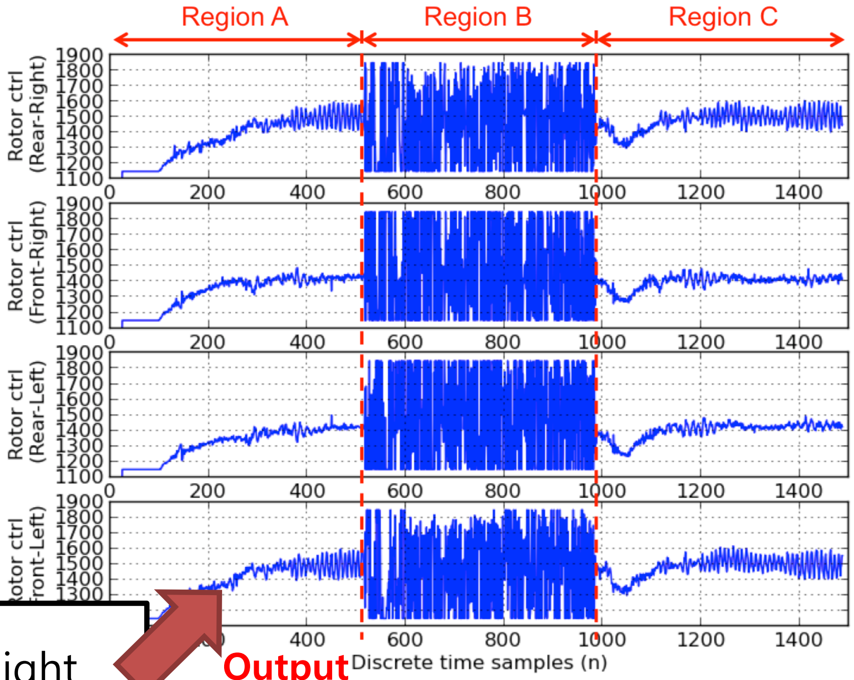


Raw data samples of the gyroscope

Input

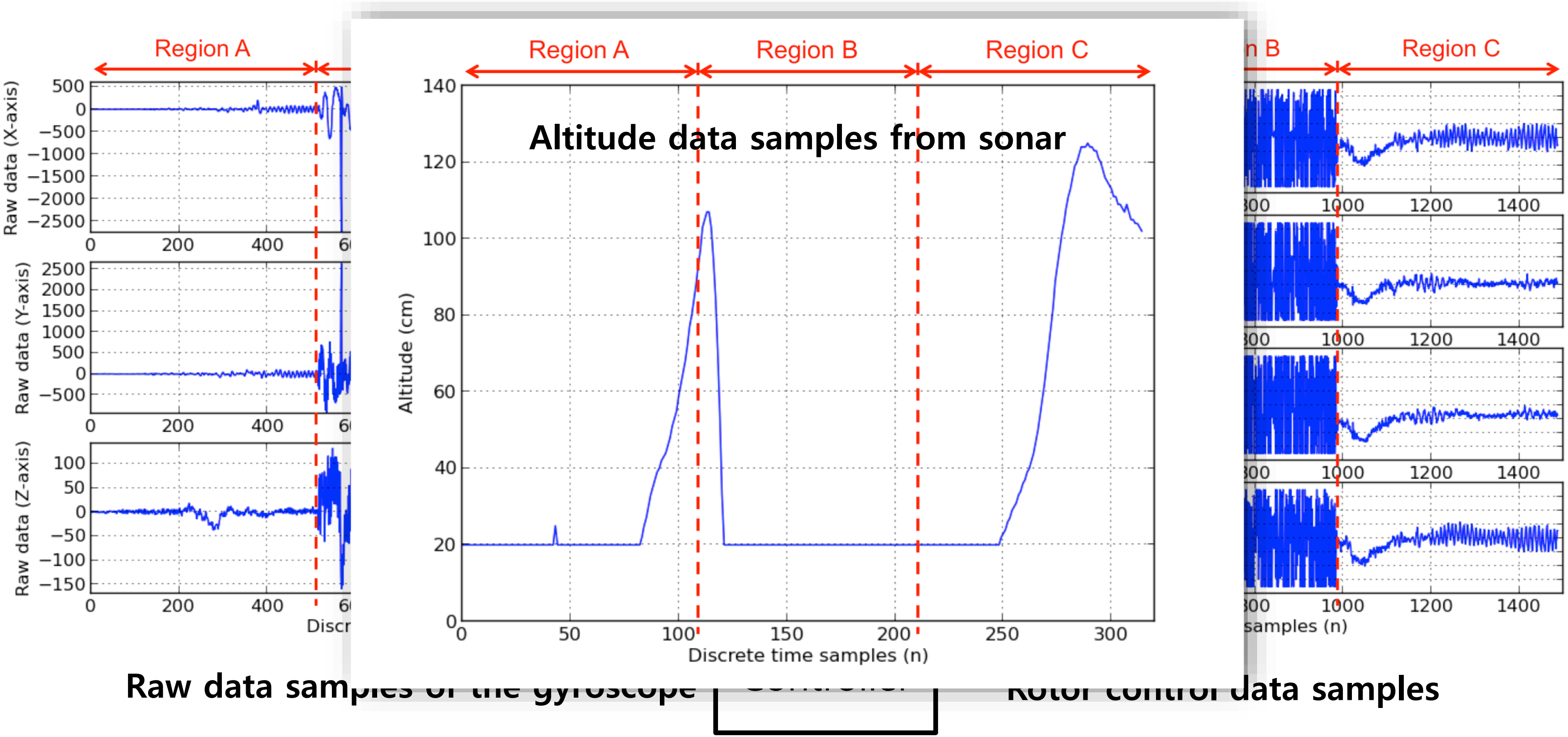
Flight Controller

Output



Rotor control data samples

Attack DEMO (Target drone A)



Attack Results

❖ Result of attacking two target drones

	Target Drone A	Target Drone B
Resonant Freq. (Gyro.)	8,200 Hz (L3G4200D)	26,200 Hz (MPU6000)
Affected Axes	X, Y, Z	Z
Attack Result	Fall down	-

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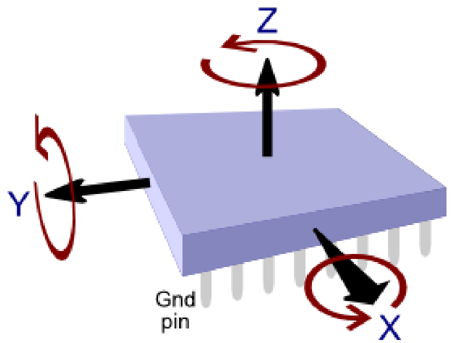

- X- and Y-axis = vertical rotation (more critical effect on stability)
- Z-axis = horizontal orientation

Attack Distance

- The minimum sound pressure level in our experiments
  - About 108.5 dB SPL (at 10cm)

$$SPL = SPL_{ref} - 20\log\left(\frac{d}{d_{ref}}\right)$$

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<450XL of LRAD Corporation>

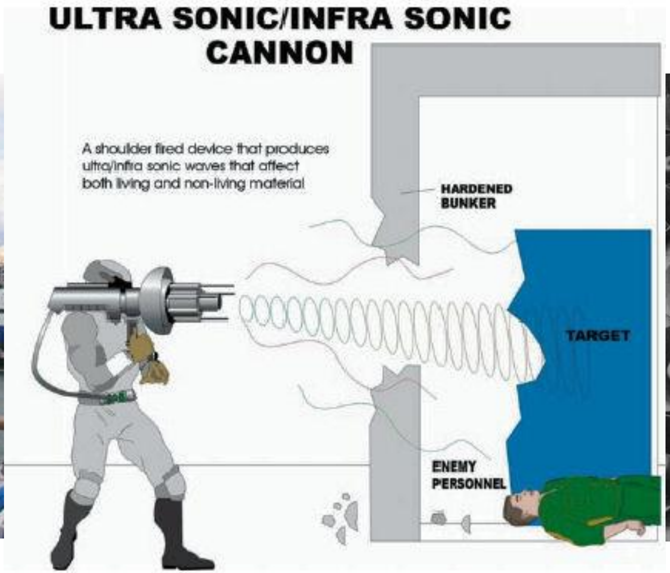
ACOUSTIC PERFORMANCE

Maximum Continuous Output	146dB SPL @ 1 meter, A-weighted
Sound Projection	+/- 15° at 1 kHz/-3dB
Communications Range	Highly intelligible voice messages over

(http://www.lradx.com/wp-content/uploads/2015/05/LRAD_Datasheet_450XL.pdf)

Attack Scenarios

- ❖ Drone to Drone Attack
- ❖ Sonic Weapons
- ❖ Sonic Wall/Zone



SysSec
System Security Lab

Limitations (1/2)

❖ Aiming at a 3- dimensional moving object

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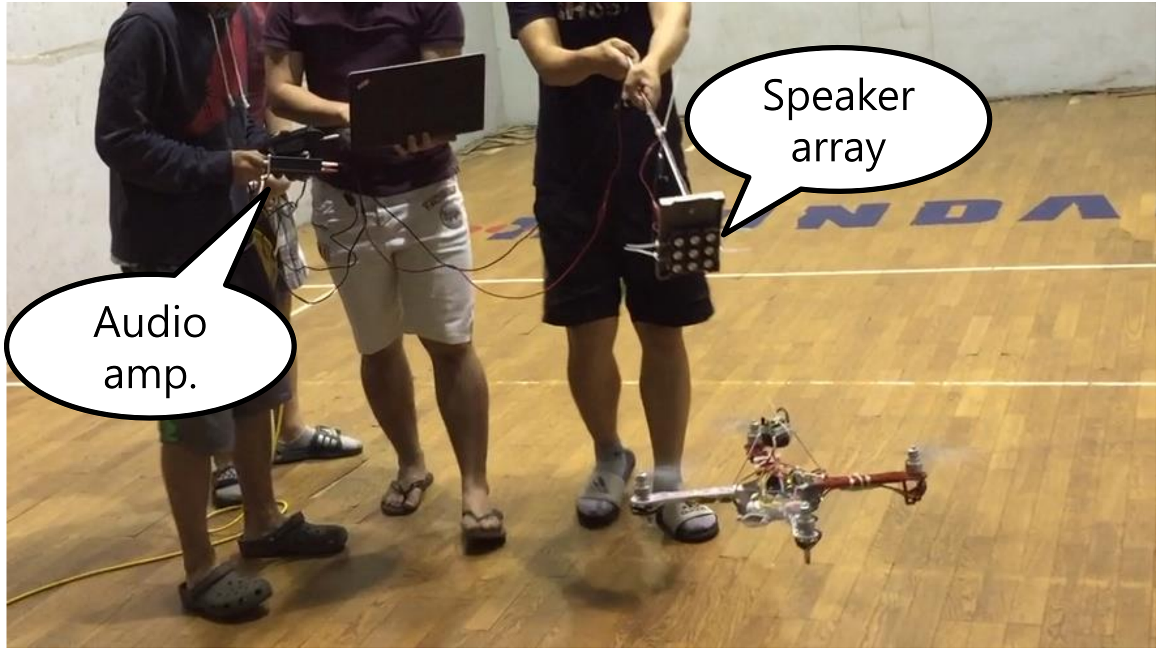

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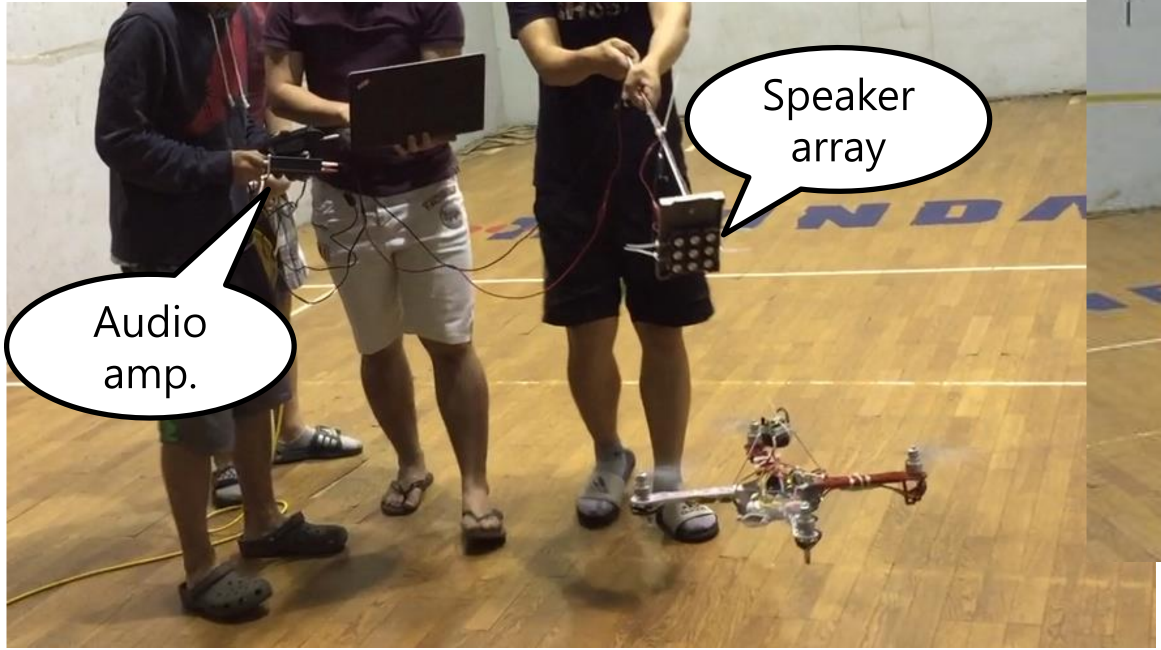

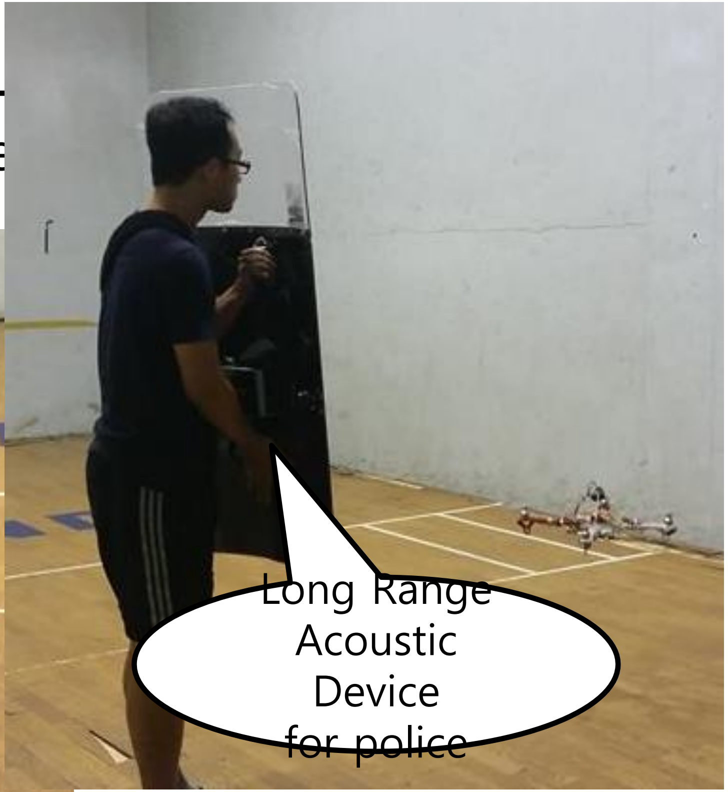

Limitations (2/2)

❖ No accumulated effect or damage

Simple sonic wall
(3m-by-2m, 25 speakers)

Countermeasure

Countermeasure

- Physical isolation
  - Shielding from sound
  - Using four materials
    - Paper box
    - Acrylic panel
    - Aluminum plate
    - Foam

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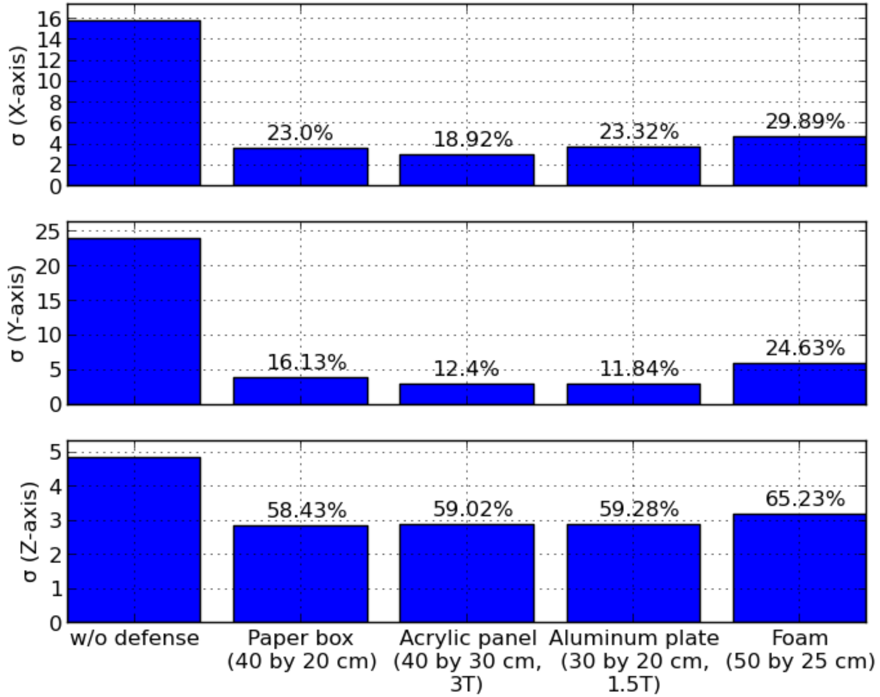
Standard deviation of raw data samples for one L3G4200D chip (averaged for 10 identical tests)



Conclusion

- A case study for a threat caused by sensor input
  - Finding mechanical resonant frequencies from 7 kinds of MEMS gyro.
  - Analyzing the effect of this resonance on the firmware of drones
  - Demonstrating to attack drones using sound noise in the real world
  - Suggesting several attack scenarios and defenses

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- Future work
  - Developing a software based defense (without hardware modifications)
  - Against sensing channel attacks for drones or embedded devices

Conclusion

- A case study for a threat caused by sensor input
  - Finding mechanical resonant frequencies from 7 kinds of MEMS gyro.
  - Analyzing the effect of this resonance on the firmware of drones
  - ld

Sensor output should not be fully trusted.

(Not only by natural errors, but also by attackers)

- Future work
  - Developing a software based defense (without hardware modifications)
  - Against sensing channel attacks for drones or embedded devices

Thank You!

yunmok00@kaist.ac.kr

APPENDIXES

Sensor

- Definition
  - To detect physical properties in nature
  - To convert them to quantitative values

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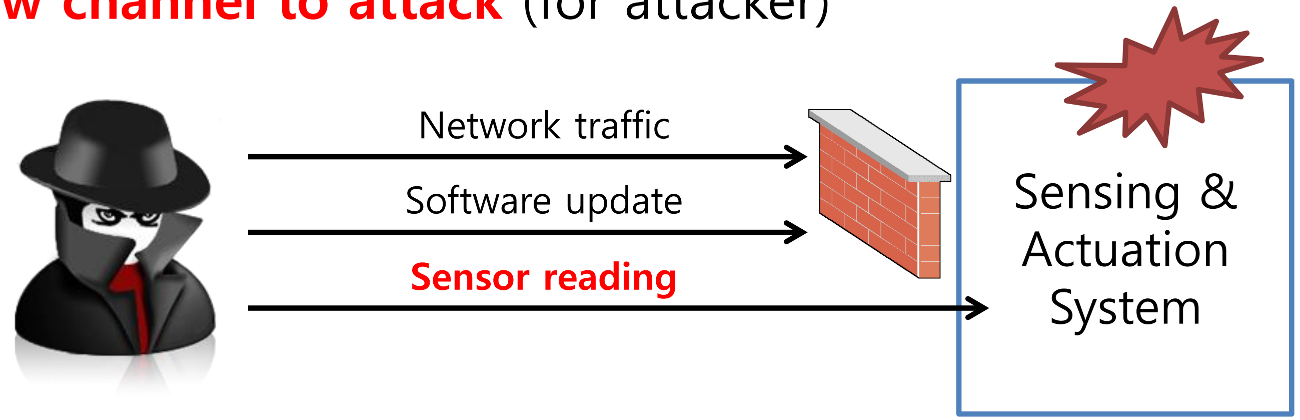
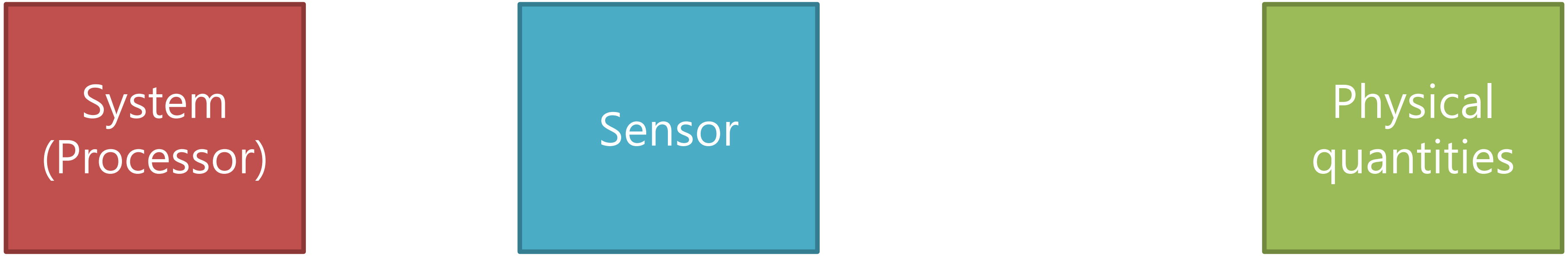


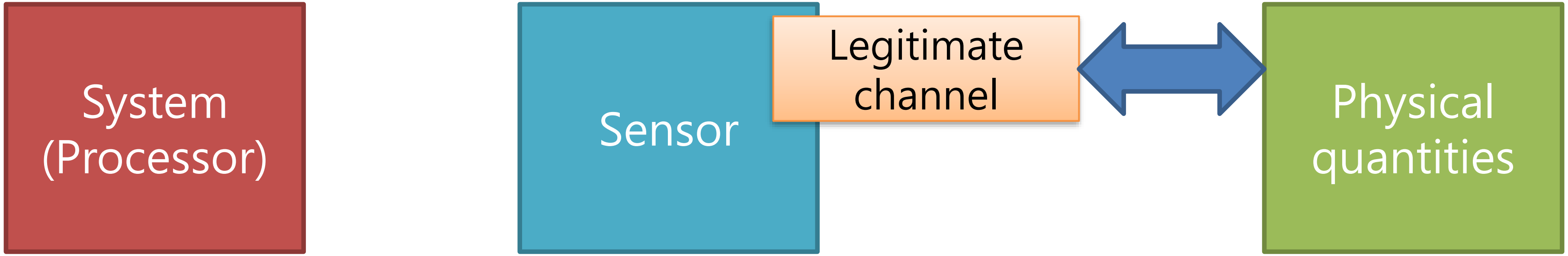
Attack Vectors of Sensor

- Three interfaces



Attack Vectors of Sensor

- Three interfaces
  - Sensitive to legitimate (physical) quantities



Attack Vectors of Sensor

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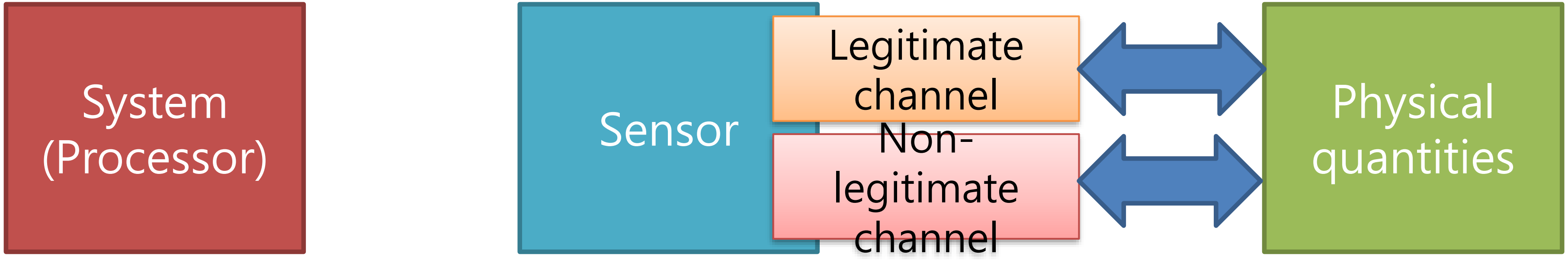

Attack Vectors of Sensor

- Three interfaces
  - Sensitive to legitimate (physical) quantities
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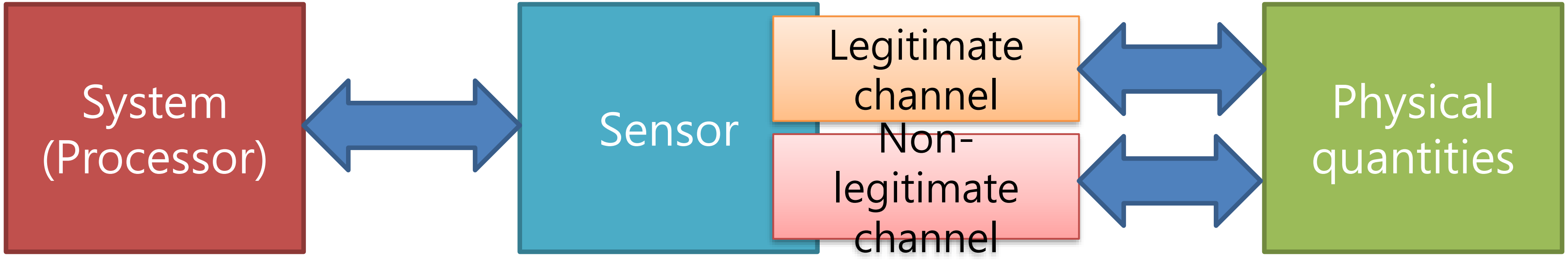
  - Need to send data to the system



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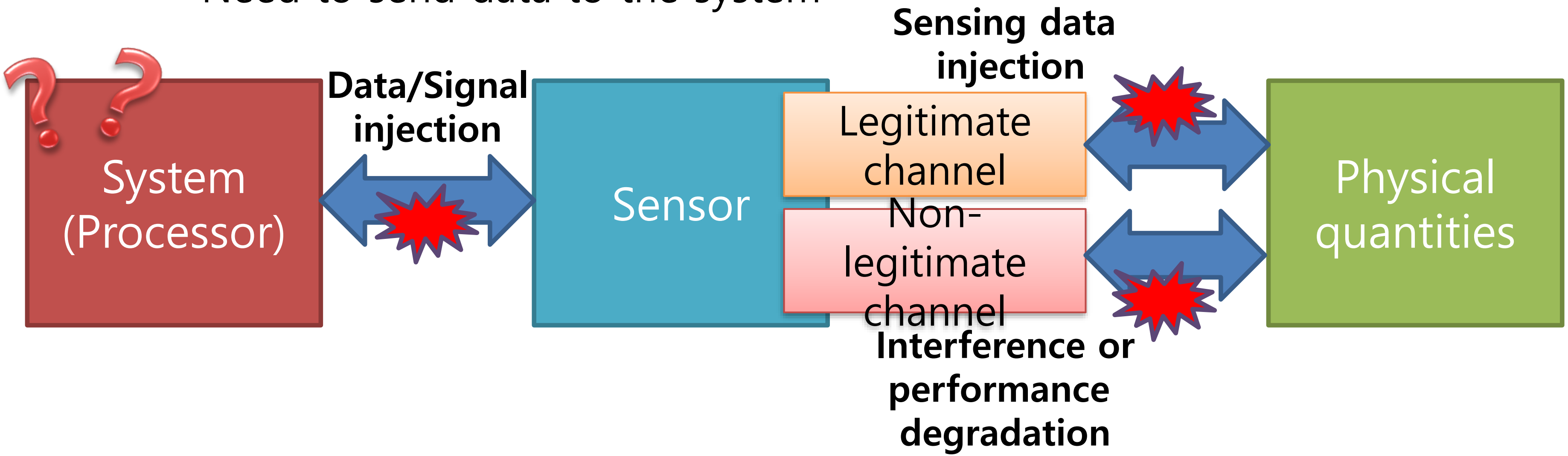

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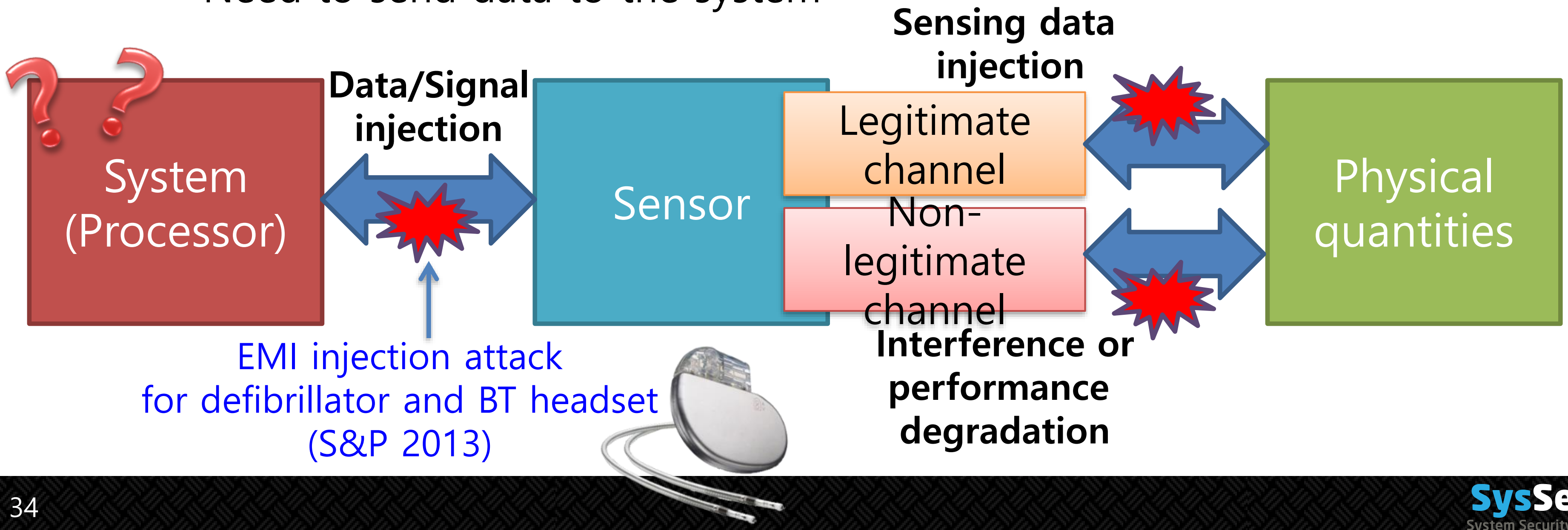

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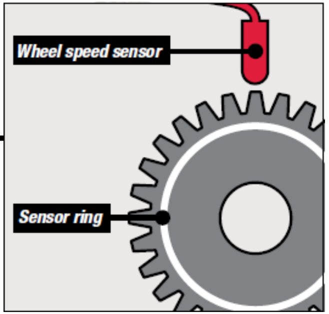

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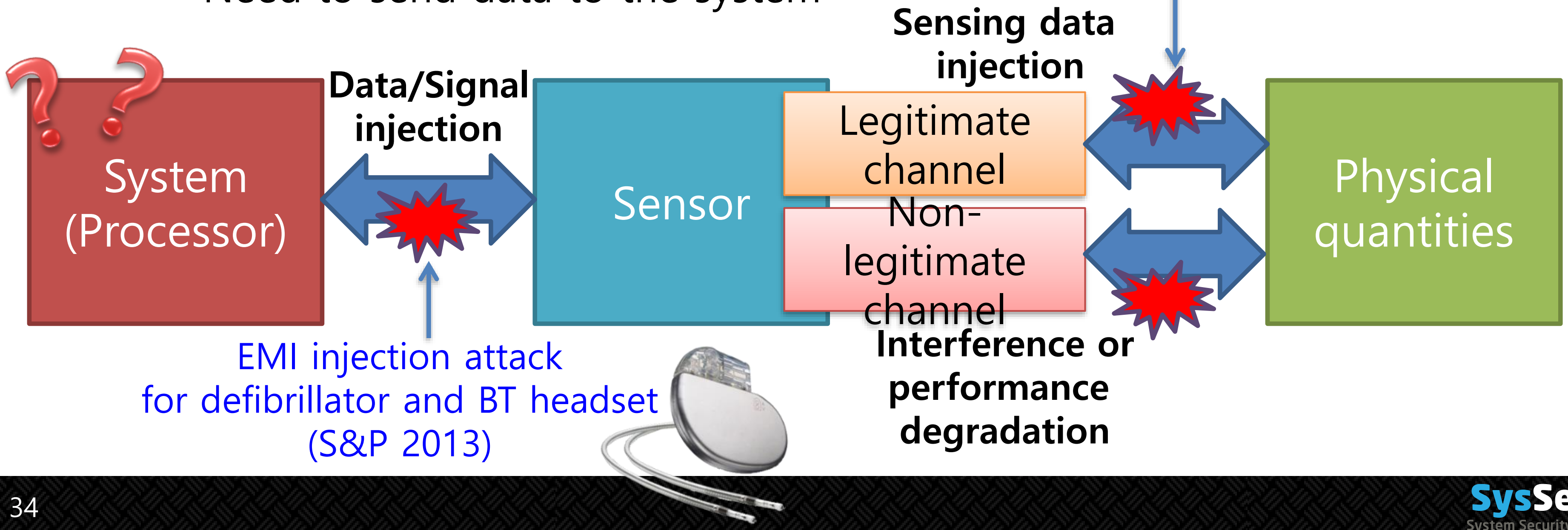

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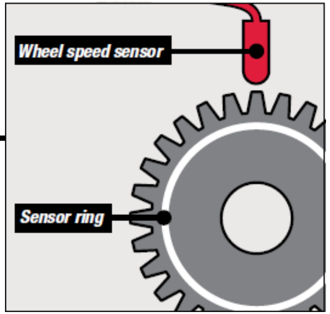

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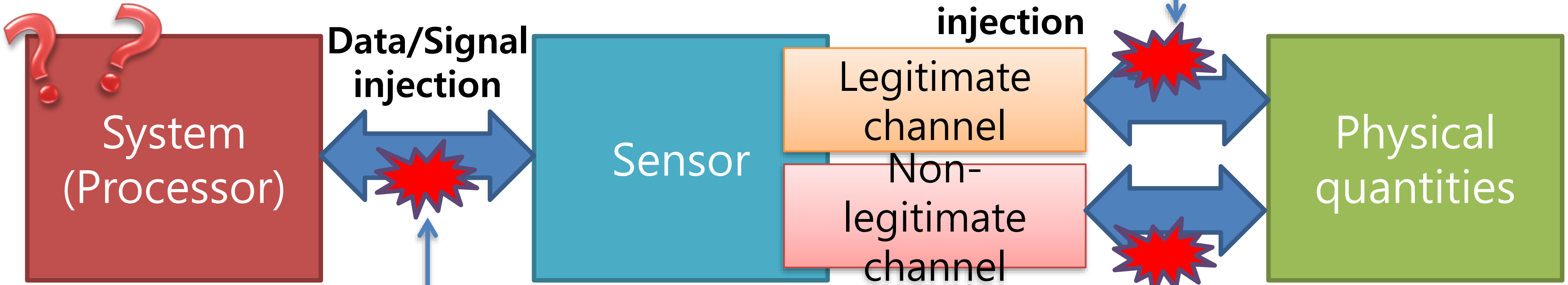
Spoofing attack for ABS in a car (CHES 2013)

Sensing data injection

Data/Signal injection



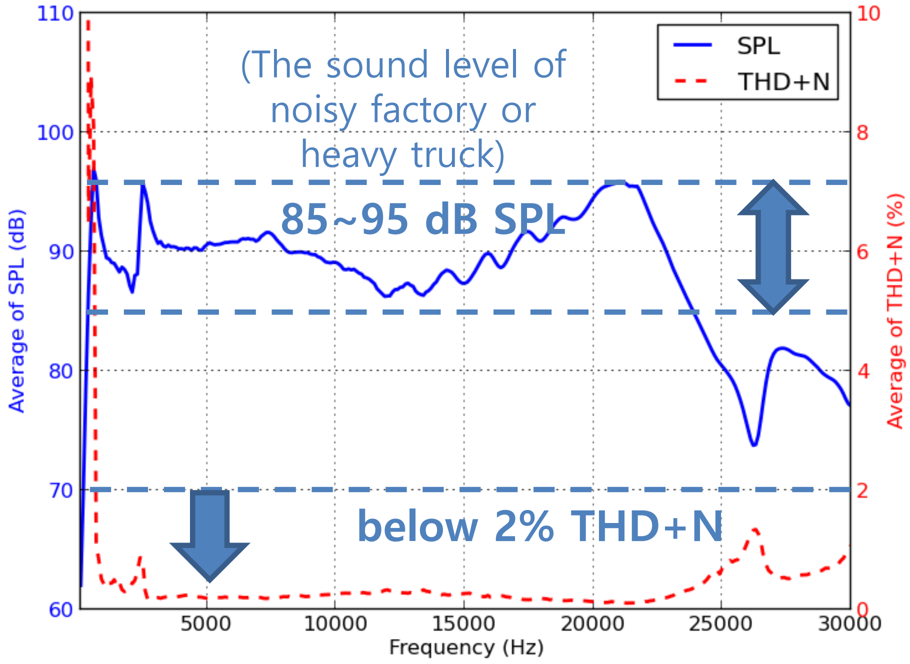
Interference or performance degradation

EMI injection attack for defibrillator and BT headset (S&P 2013)

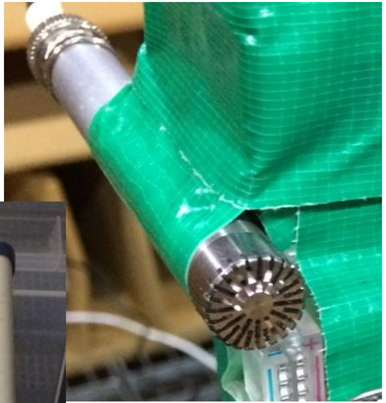
Our work

Sound Noise Source

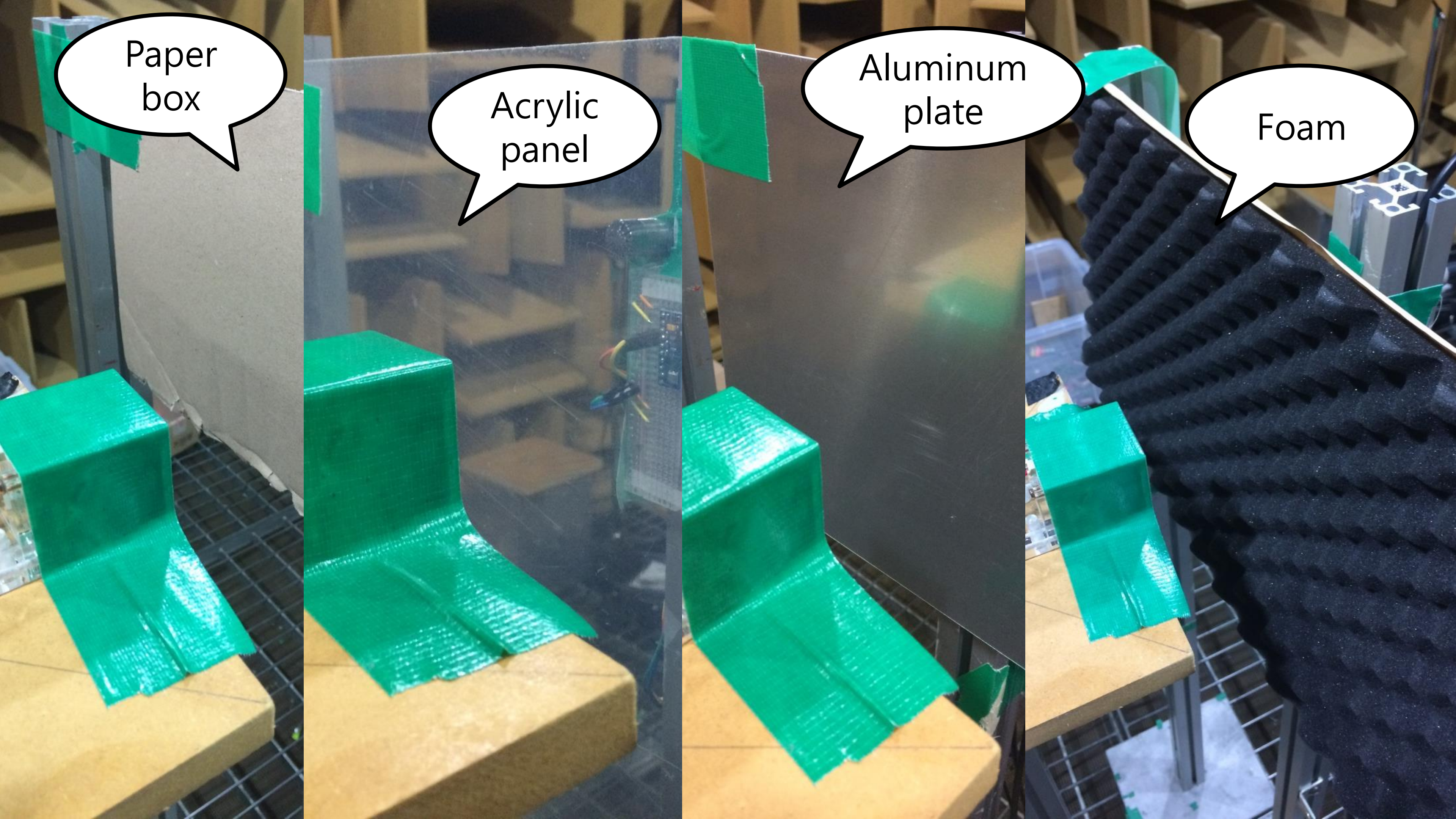
- Sound Pressure Level (SPL) and Total Harmonics Distortion plus Noise (THD+N) measurement



Microphone (Brüel & Kjær 4189-A-021)



Sound Measurement Instrument (NI USB-4431)


Paper box
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