Resonant Evil:

Measuring the Effect of MEMS Gyroscopes at Resonance

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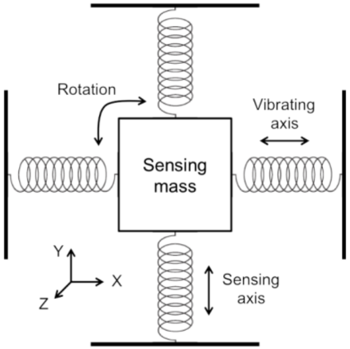
EECS 588 W18 Project

Overview

- Firing loud acoustic signals at resonant frequency at MEMS gyroscopes causes sensor to ‘freak out’
- *Rocking Drones with Intentional Sound Noise on Gyroscopic Sensors*
  - Son, et al (USENIX ‘15)
  - Effectively ‘DDoS’ drone
- This Project:
  - Analysis and experimental validation of various factors affecting gyroscope readings at resonance
  - Comment on efficacy of *Rocking Drones* in practice

Background - MEMS Gyroscopes

- MEMS - Microelectronic Mechanical Systems
  - Uses spring model to sense roll, pitch, yaw
- Different gyroscopes react differently at different frequencies
  - Most MEMS gyros have *resonant* frequencies
- At resonance, some sensing axes exhibit large swings in amplitude

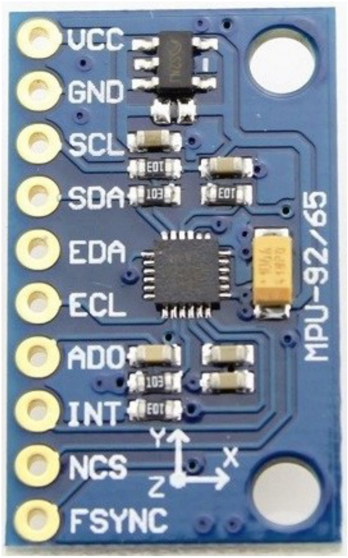


Methods

- Run experiments to determine response of gyroscope in various environments
- Specifically, effect of:
  - Distance of speaker from gyroscope
  - Orientation of speaker to gyroscope
  - Dampening materials
- Additionally, test efficacy of rocking drones

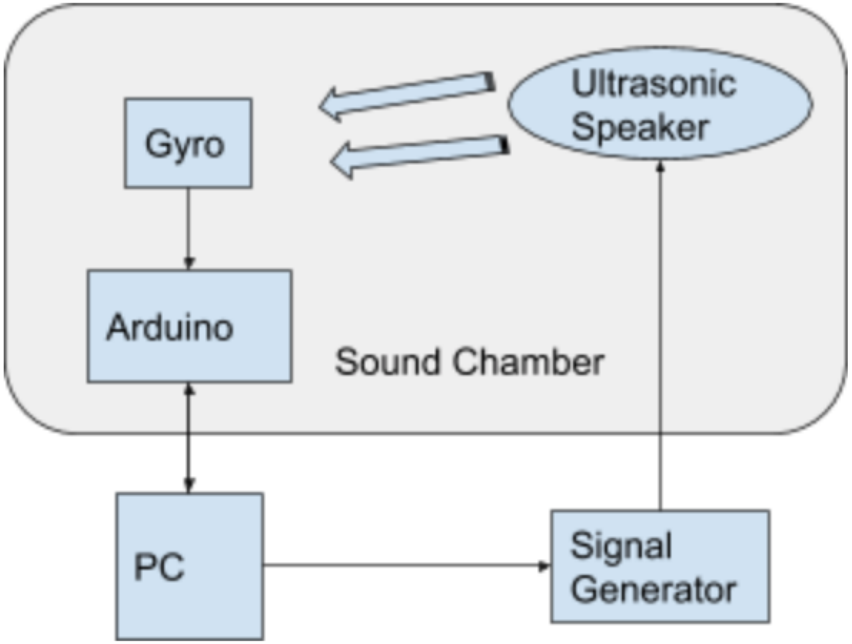
Methods

- Used MPU9250 IMU in all experiments
- MPU9250 popular IMU for embedded systems
  - various smartphones
  - AR/VR/robotic sensing devices
  - *DRONES!*
- Requires custom firmware to run

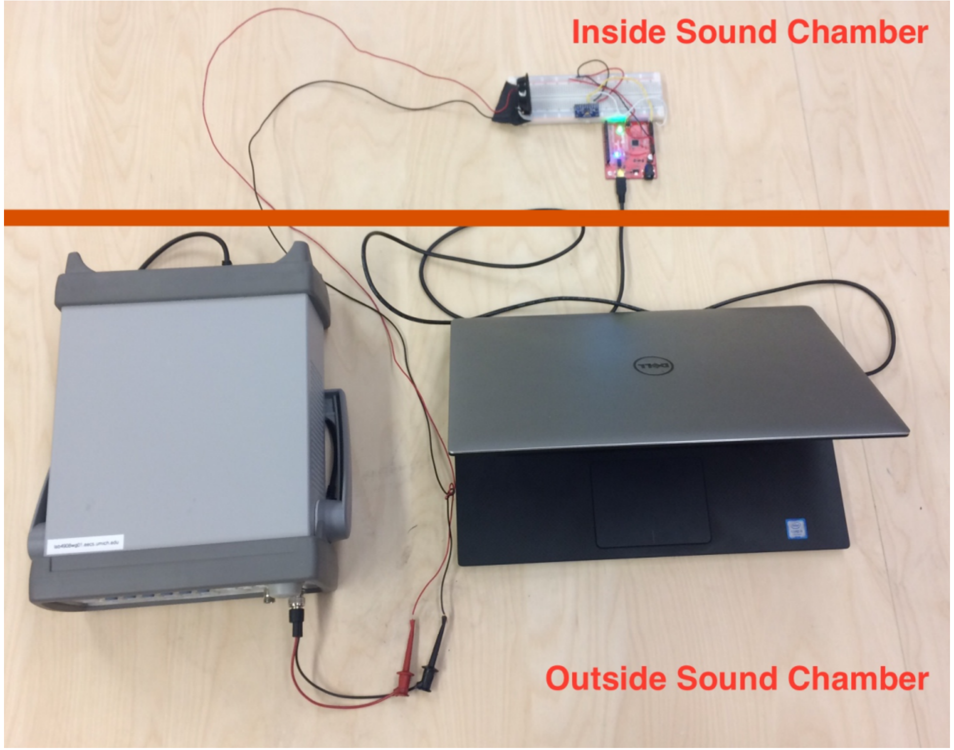


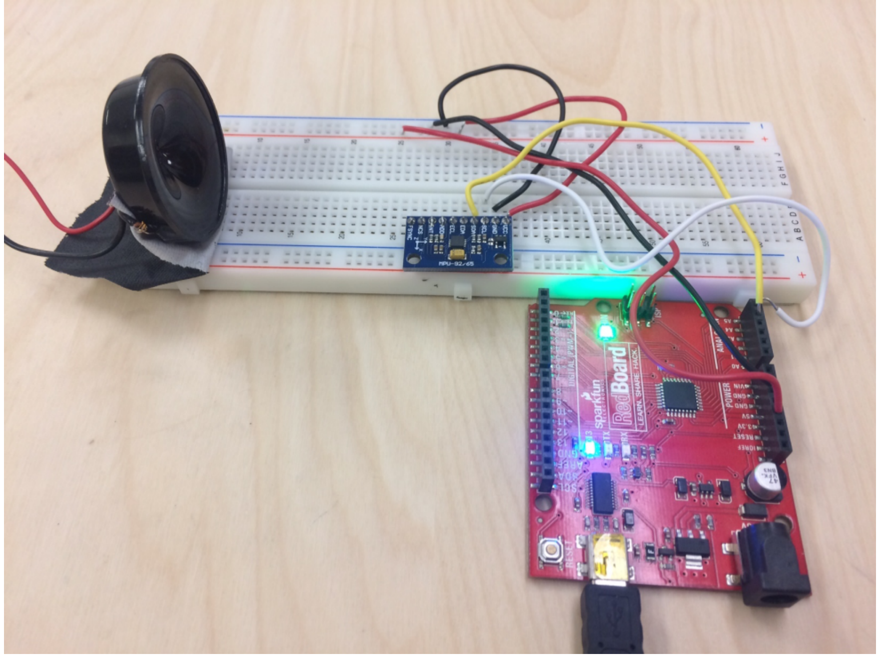
Experimental Setup

- Ultrasonic speaker pointed at gyroscope
  - Signal generator used to generate frequency
  - Physically decoupled
- Arduino interface to gyroscope
  - Gyro sends data over I2C
  - Sends data to PC over USB serial
- PC workstation oversees experiment
  - Python script sets signal generator frequency, Vppk
  - Collects and logs gyro data



Experimental Setup





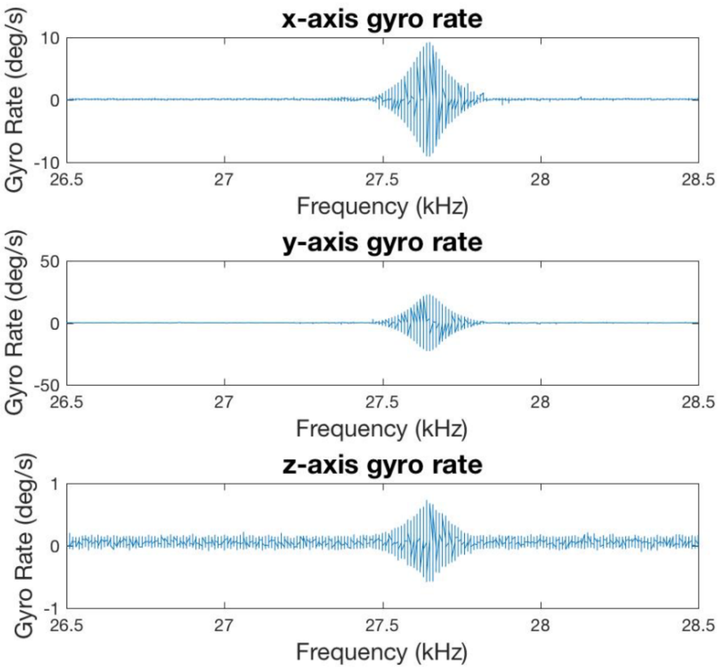
Results - Data Collection

- Initial data collection was promising!
- Frequency sweep around resonance stated in datasheet - 10 Hz increments
- MPU9250 resonance around 27.66 kHz

NOTE! Resonance will change based on mechanical coupling, PCB mounting, etc

NOTE! Amplitude also affected by reverberations of signal against chamber walls, surfaces, etc.

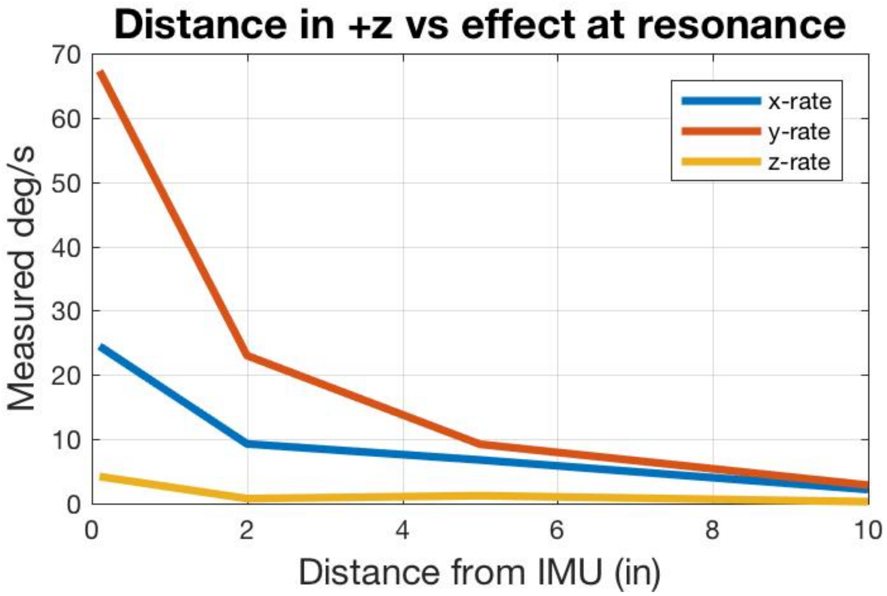
- Y-axis (pitch) largely affected
- Z-axis (yaw) minimally affected



Raw data trace taken with speaker 2 inches from gyroscope in Z direction

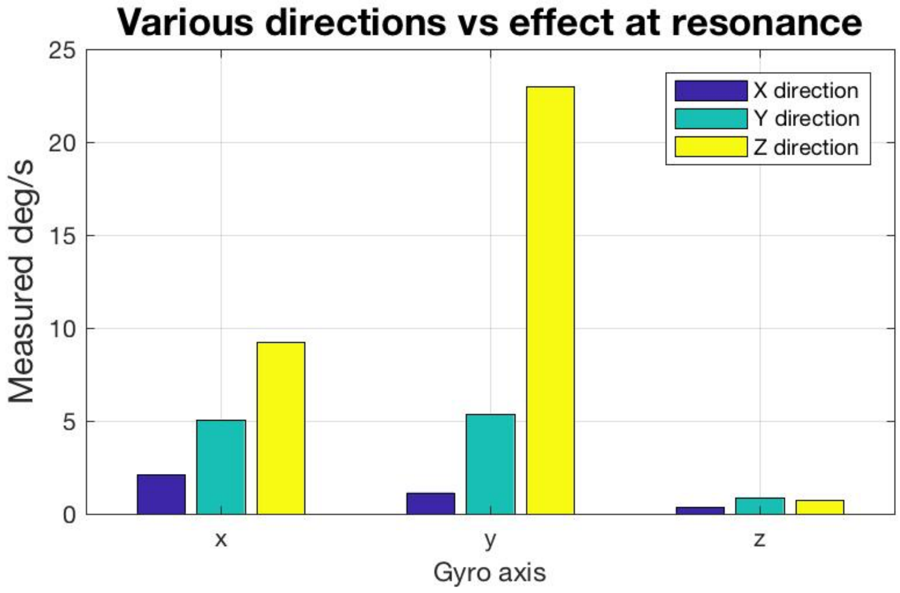
Results - Speaker Distance from Gyro

- Placed speaker at various distances from gyroscope
  - As close as possible
  - 2 inches away
  - 5 inches away
  - 10 inches away
- Max amplitude attenuated down exponentially as distance increases
  - Gyroscope angular rates proportional to amplitude of speaker
  - Indirectly proves inverse square law of sound!



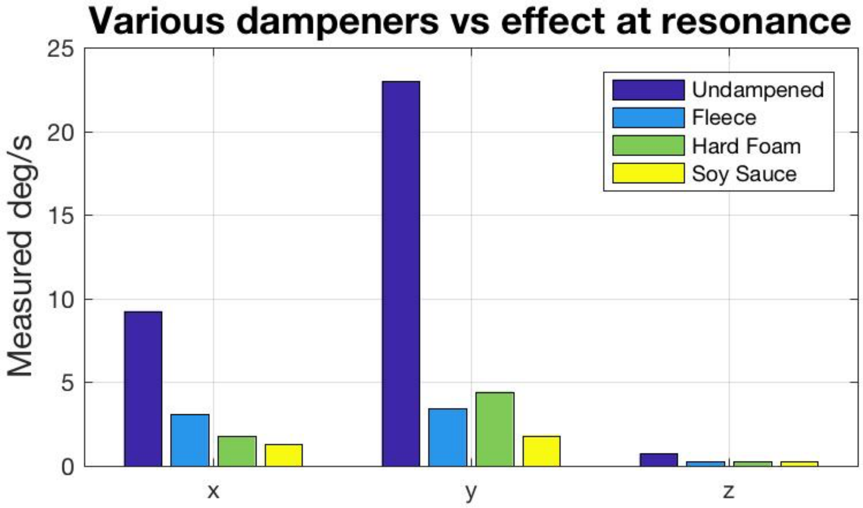
Results - Orientation w.r.t. Gyroscope

- Kept speaker 2 inches away from gyroscope
- Results most impressive when speaker pointed in Z direction (yellow bars)
- Other directions yielded less of a difference



Results - Effects of Dampening Materials

- Curious to see what effect various materials will have at dampening signal
- All materials have large effect in dampening effect of speaker at resonance
- Soy sauce proved to do best job
    - Low viscosity liquids yield low bulk modulus (ability to compress)



Data traces taken with speaker 2 inches from gyroscope in Z direction

Results - Takeaways

- Affecting gyroscope angular velocities quickly becomes difficult the farther a speaker is from the IMU
- Speaker must be positioned in a certain direction for optimal effect
  - Other directions cause large attenuation from optimal
- Most any material placed between sound source and gyroscope will decrease effect of resonance

Results - Rocking Drones

- Initial plan - *Rocking Drones* with physical decoupling
- Testing with racing drone, same IMU as tested (MPU9250)
- Flight controller software finicky, large movements with minimal input
  - Built for racing

Flying the drone

Results - Rocking Drones

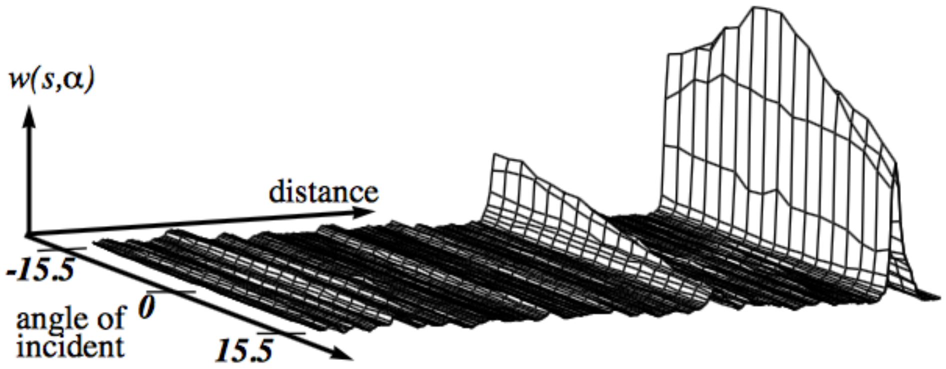
We qualitatively evaluate the efficacy of *Rocking Drones* as it applies to real-world drones

1. Drones very high speed (~20 m/s)
    - Gyroscope reading dropoff already large at 0.3 m
2. Directionality not guaranteed optimal
    - Further dropoff from quaternion of drone wrt speaker
3. Gyroscope package covered in housing
    - Ultrasonic waves greatly dampened
4. Flight control software uses gyroscope as one of many parameters in state estimation
    - In perfect conditions, not guaranteed to rock drone
5. Need to calibrate signal frequency often
    - Moving drone means doppler effect on gyroscope - different observed frequency

Overall efficacy: Very Poor

Future Directions

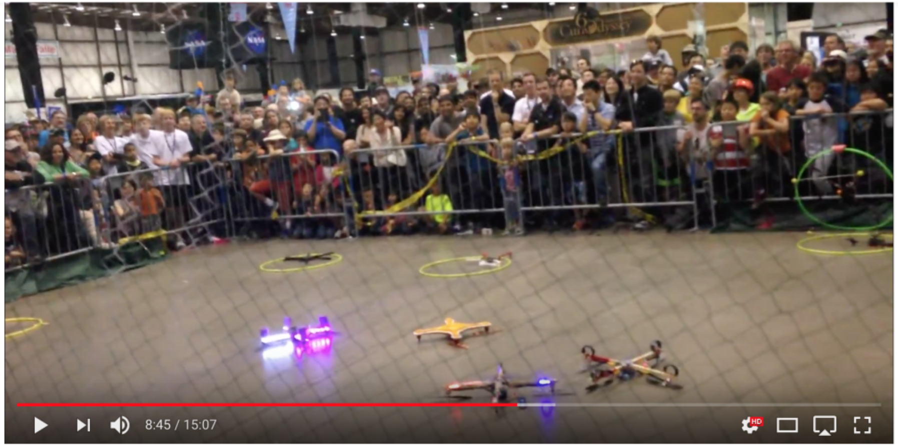
- Sonic beamforming to preserve power
  - Beams propagate longer
- Explore possibility of controlling drone via gyroscope
  - Controlling readout a la *WALNUT*



Ultrasonic Beamforming Principles, Suoranta (1992)
w is the amplitude seen at given distance and angle

Future Directions

- Have attack drone get near victim, with speaker pointed away from gyroscope
    - Most drone rigs naturally set up to attenuate backpropagating noise
    - Initial tests promising! - readout stable around zero deg/s
    - Speaker must be physically decoupled (e.g. via suspension)
    - Interesting use case in drone fighting



Maker Faire 2014 - Game of Drones - Final Fight - Royal Rumble Style

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Conclusion

- Described how MEMS gyroscopes work
- Ran experiments on physical gyroscope
    - Effects of speaker distance to IMU
    - Effects of direction w.r.t. IMU
    - Effects of damping
- Commented on efficacy of *Rocking Drones* via results
    - Very poor!
    - Iron Dome still seems to be best at rocking drones
        - Fire a rocket at the victim!

Thank You

WHELP DRONEZ ARE STILL STABLE
BUT WE GOT REALLY COOL PARAMETERS
FOR GYROSCOPE HACKZ!
imgflip.com

LOST DRONE
RESPONDS TO "SPIKE"
MAY DISPLAY AGGRESSION, APPROACH WITH CAUTION
LAST SEEN OVER THAYER & POWER STREETS
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