Temperature-Bias Compensation of Low-Cost Inertial Sensors – Possible or Pipe Dream?

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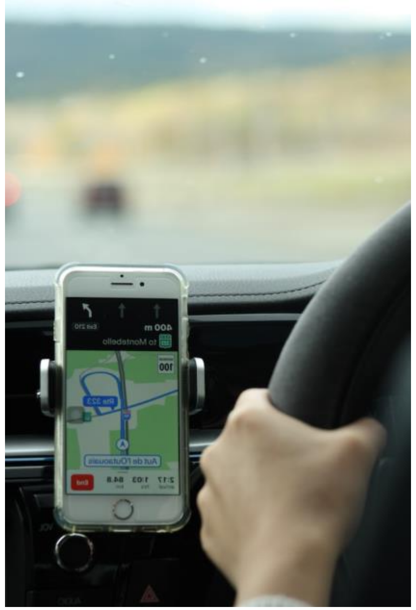
Introduction – Your journey here (1)



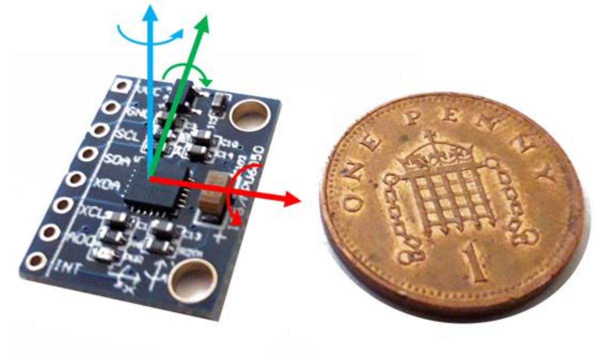
- How did you navigate to this conference?
  - Drive with help from your smartphone.
  - Take a flight.
  - Use visual cues (landmarks, signs etc.) and memory (hippocampus).

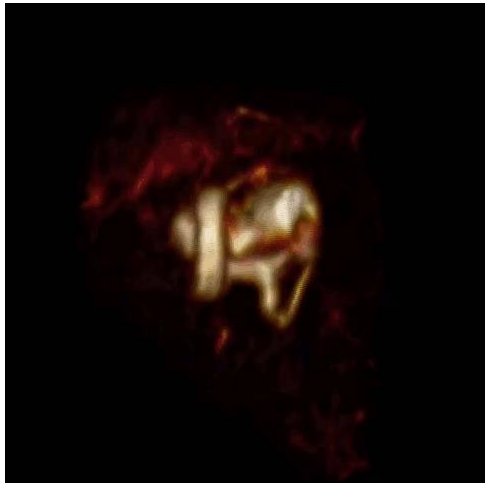
GPS

Exteroceptive

Introduction – Your journey here (2)

- Inertially navigate?
  - Sensing accelerations and rotations via the vestibular system.
  - You likely used your vestibular system more for stability than navigation.
  - How long would you trust navigating by your vestibular system alone?
- The same issues are faced in man-made inertial sensors (accelerometers and gyroscopes):
  - For low-cost sensors (e.g. MPU-6050 sensor package), error in positional estimate accumulates exponentially with time.

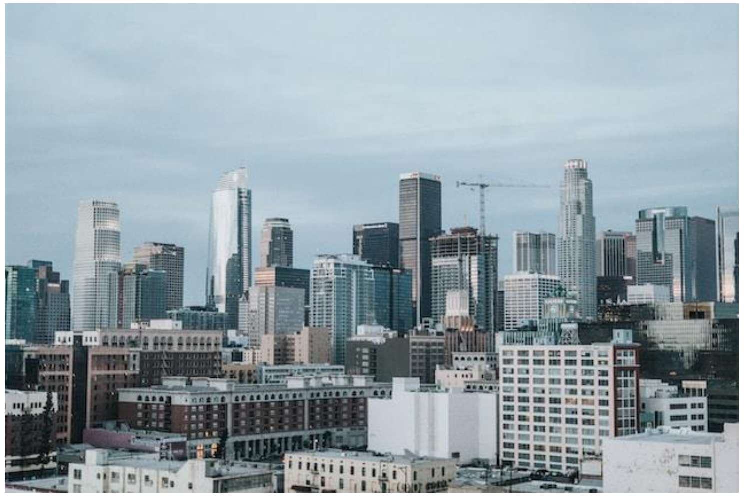




"Cochlea and vestibular system" by Nevit Dilmen (talk) is licensed under CC BY-SA 3.0.

"Blind-man's buff - Punch (22 September 1888), 139 - BL" by John Tenniel is marked with CC0 1.0.

Introduction - Why inertial navigation?

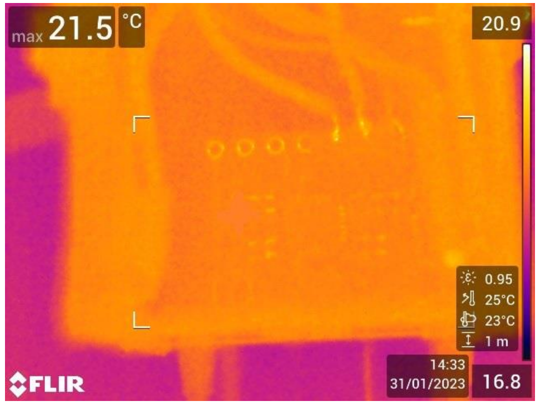


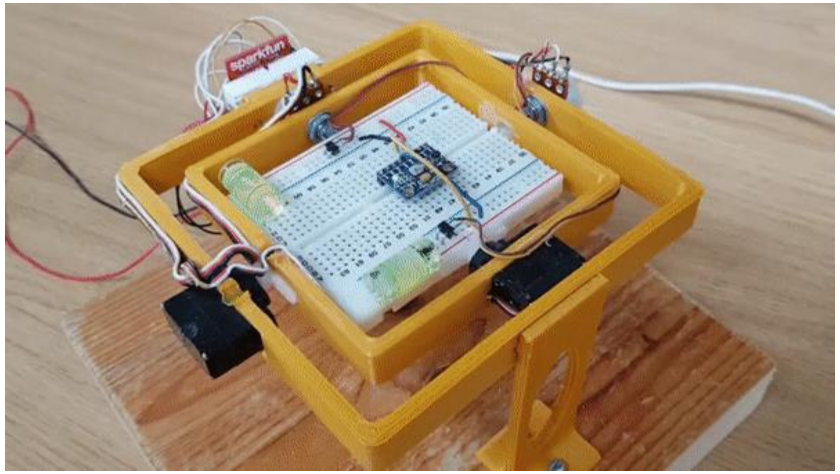
- GPS:
    - Reduced accuracy in urban canyons.
    - Loss of service indoors, underground and underwater.
    - Prone to spoofing and jamming.
- Exteroceptive:
    - Featureless spaces.
    - Edge case scenarios (dark, dusty, smoky).

Introduction – Errors Affecting Low-Cost Inertial Sensors

- Inertial sensor errors can be random or systematic.
  - Calibration of sensors can be done using a multi-positional experiment or gimbal.
  - However, calibration parameters will drift with sensor temperature (influenced by ambient temperature and self-heating).

Random:	Systematic:
Flicker noise	Cross-axis sensitivity
White noise	Scale factor temperature sensitivity
	Zero bias temperature drift



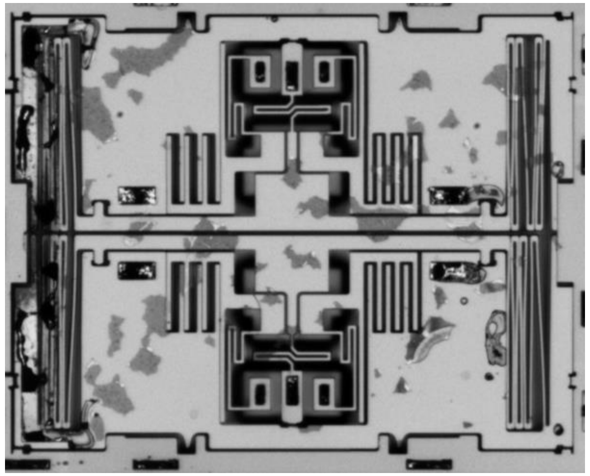


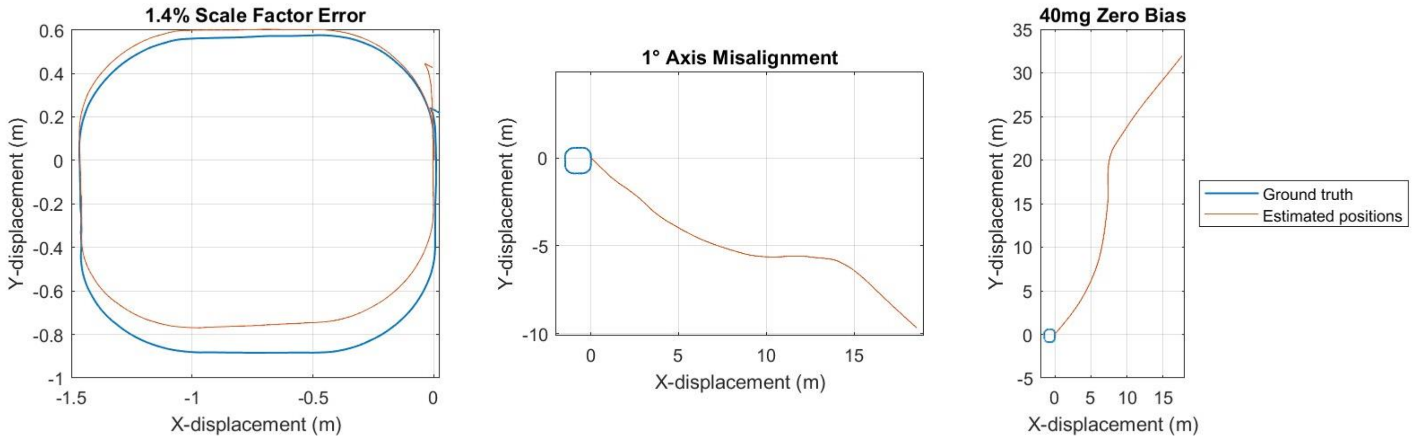
Contributions of this Work

1. The modelling of a 3-axis accelerometer to identify the most significant measurement error source.
2. Show how sensor zero biases vary for three IMUs of the same model over their operating range and for temperature cycles.
3. Show how some sensors have responses that can be fused and the bias error reduced as a result.
4. An investigation into the effect of humidity on sensor biases.
5. An investigation into the effect of sudden changes in rate of temperature change on biases.

1. Identification of Most Serious Error Contributor

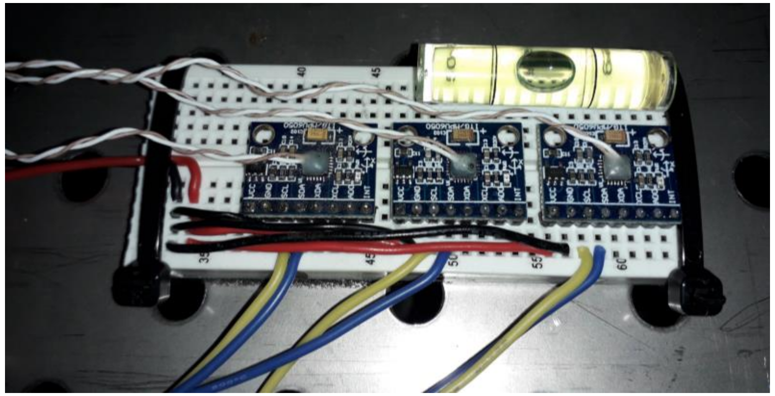
- Assumptions:
  - Consider only the accelerometer.
  - Assume is accurately modelled as a mass spring damper.
  - Typical error values for bias, scale factor and misalignment errors taken from the MPU-6050 datasheet.
- The **zero bias** was found to be the **most significant error**.

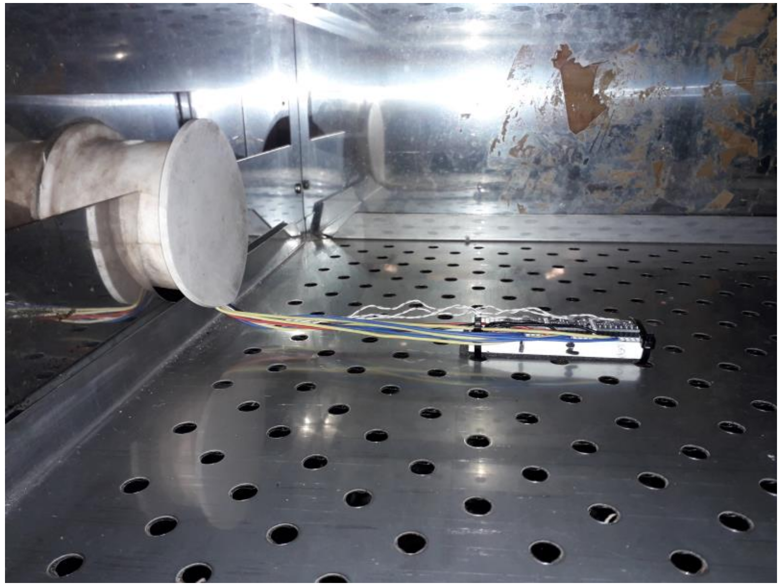




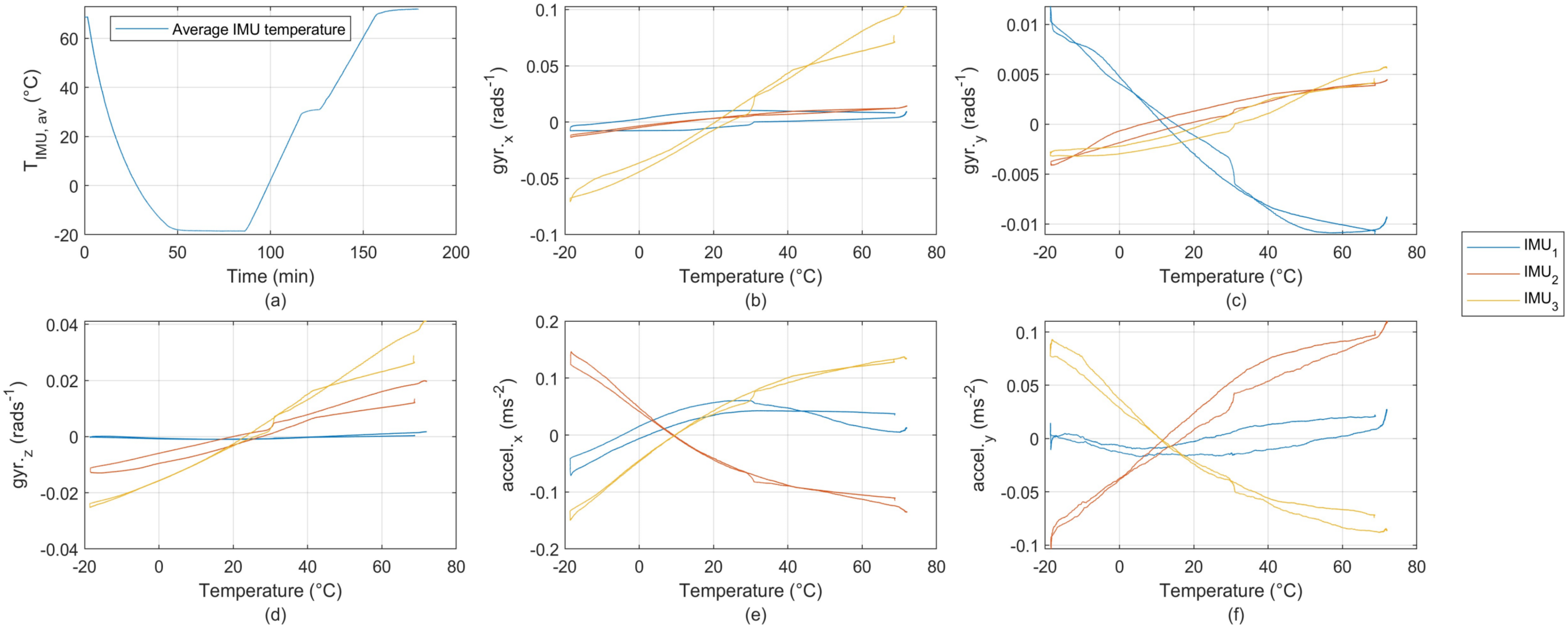
Sensor error:	Description in datasheet:	a_{mse} (ms^{-2}):
Zero bias	±40mg (between 0°C and 70°C)	**0.134**
Scale factor	±1.4% (between 0°C and 70°C)	0.030
Cross-axis sensitivity	±2%	0.042

Temperature Experiments Setup





2. IMU Zero Bias Variation with Temperature - Sweep



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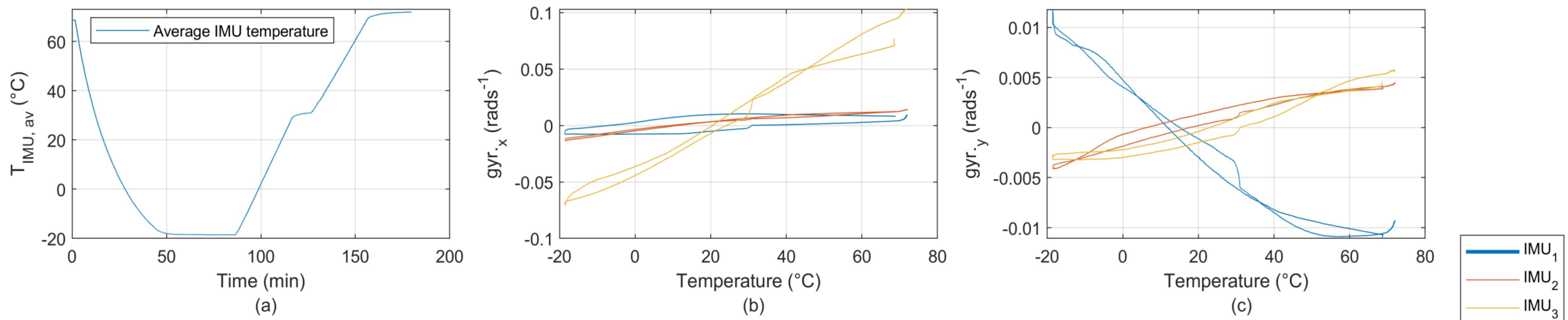
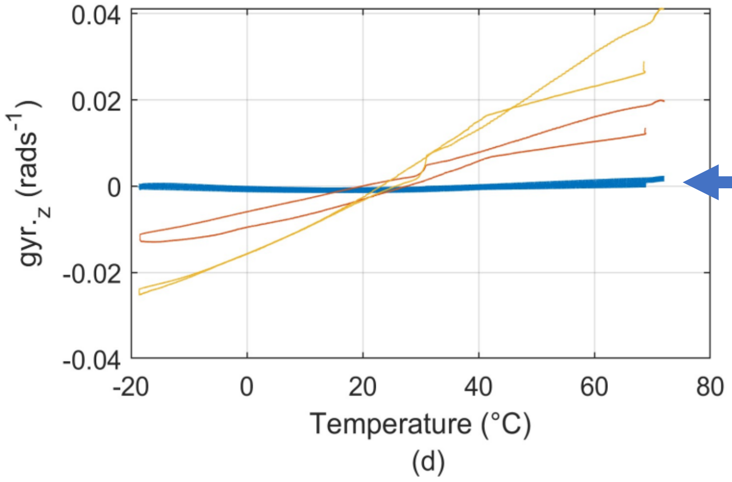
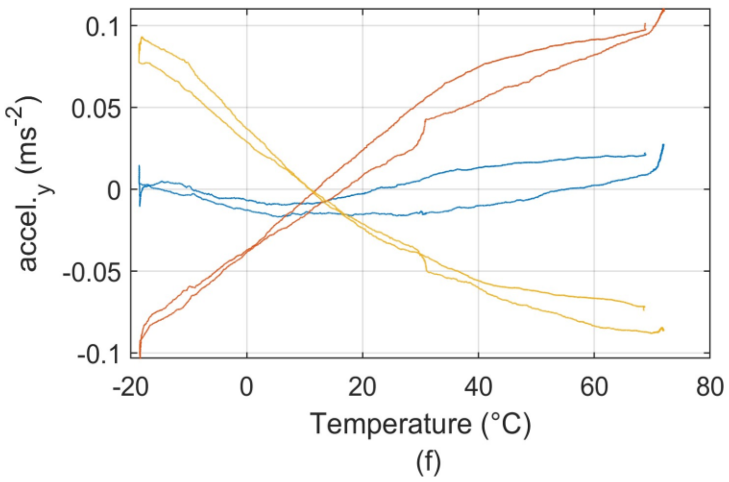




z-axis of IMU_1 has temperature-bias response ~60x lower than other axes



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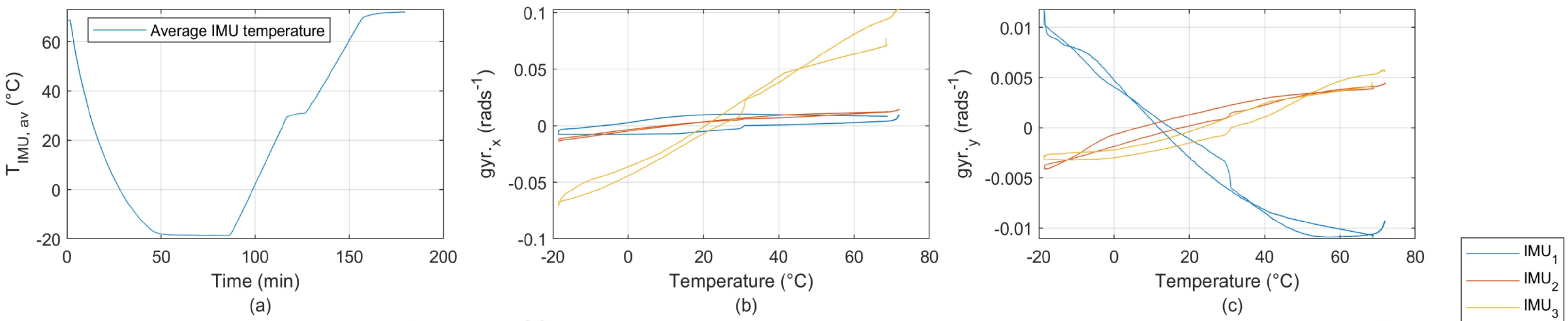
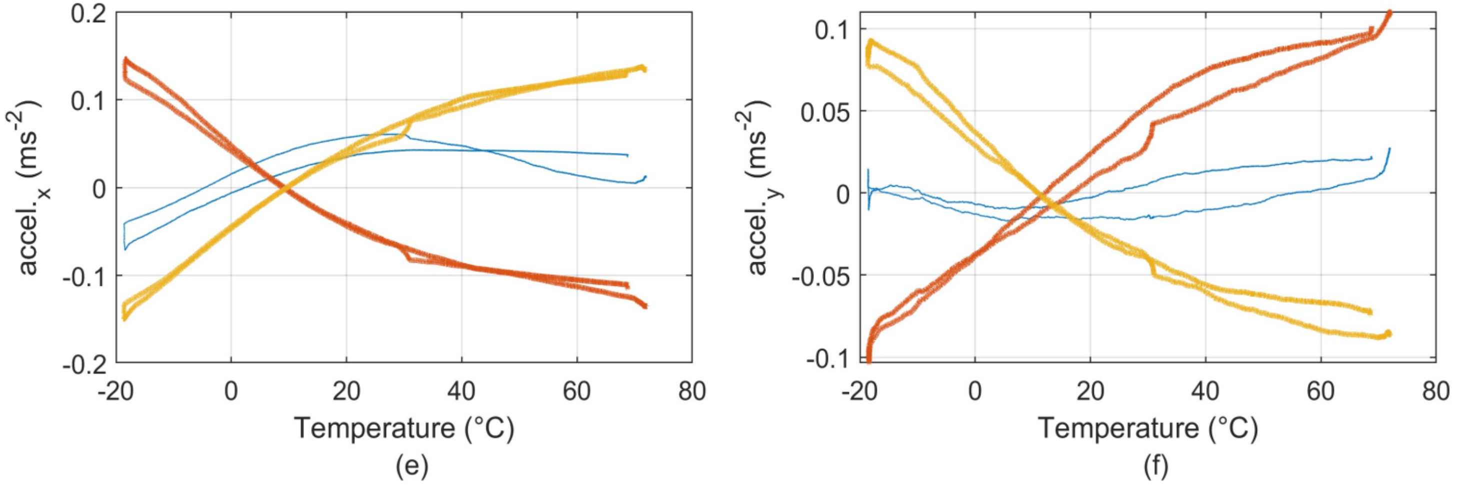
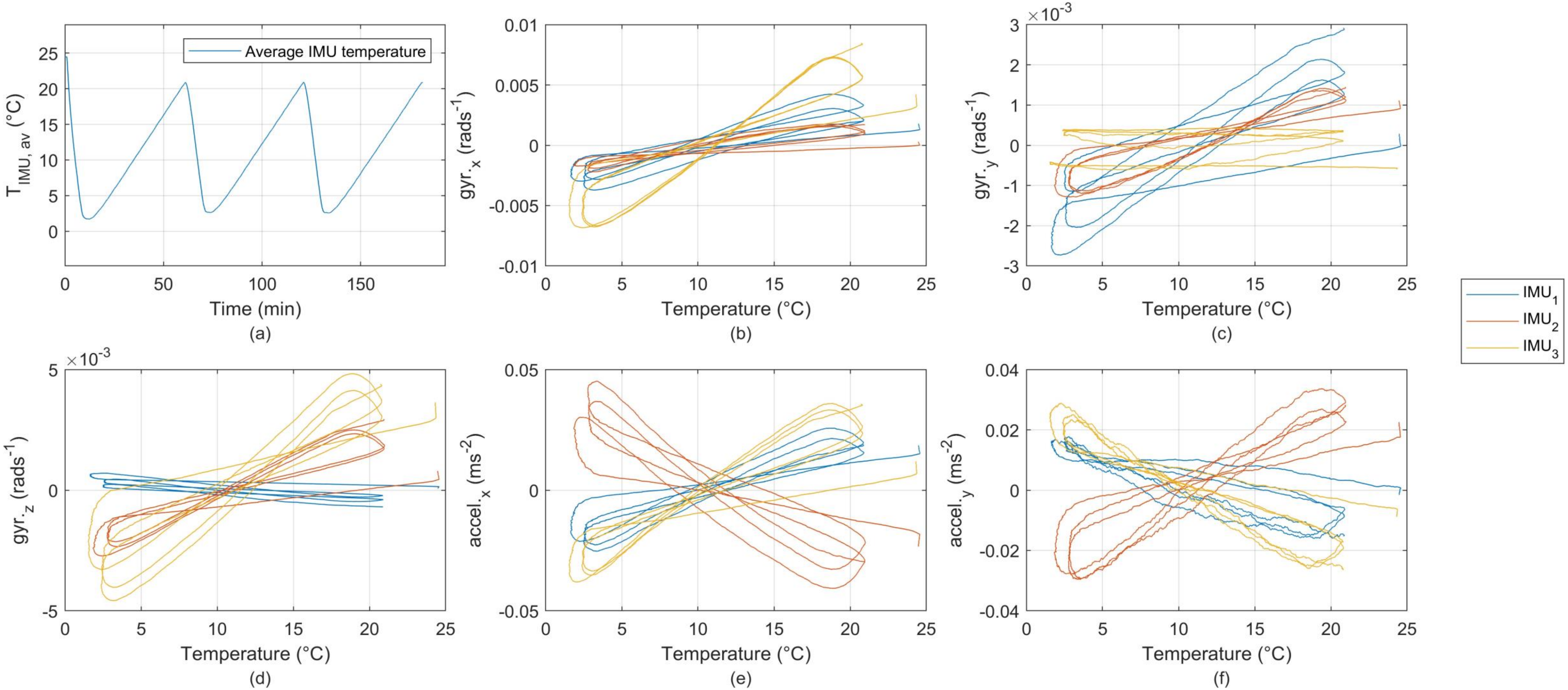


x and y axes of IMUs 2 and 3 have opposing responses



2. IMU Zero Bias Variation with Temperature - Cycles



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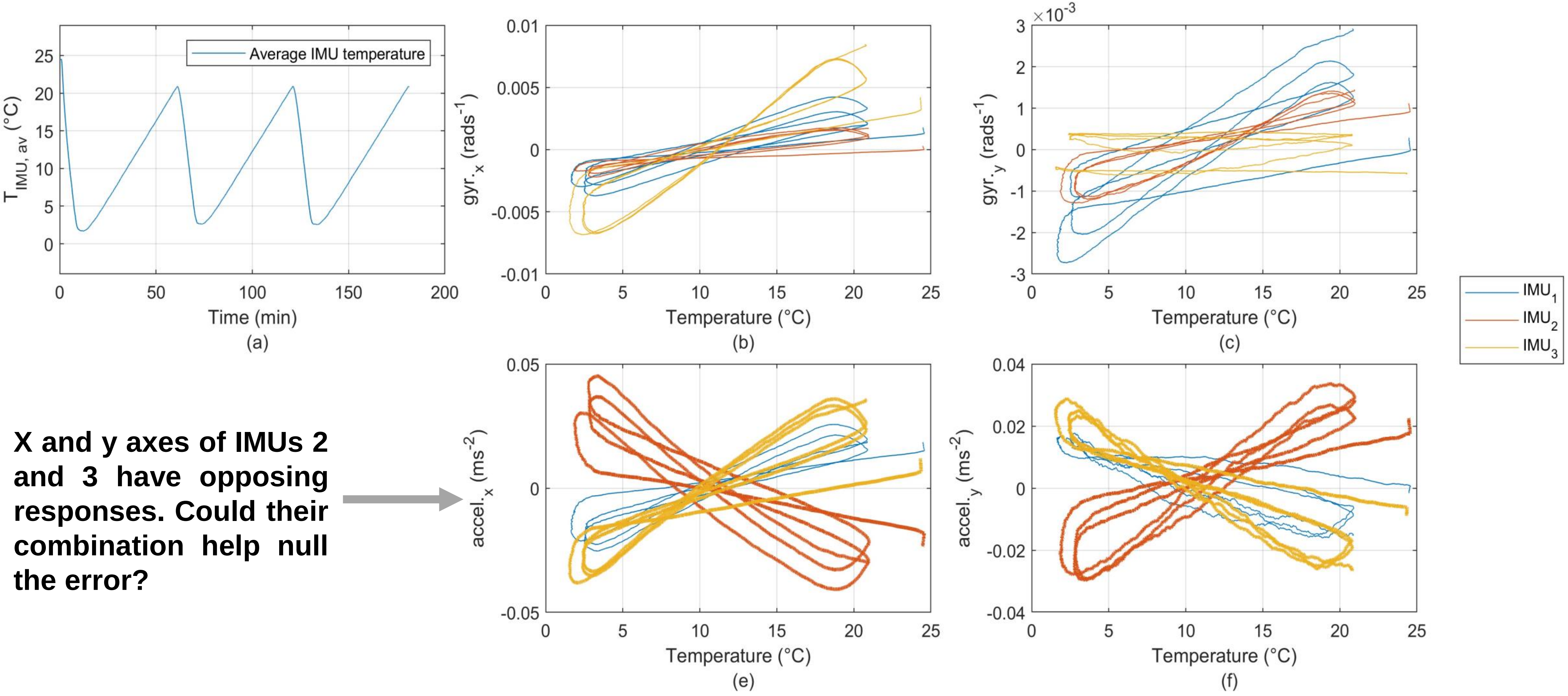
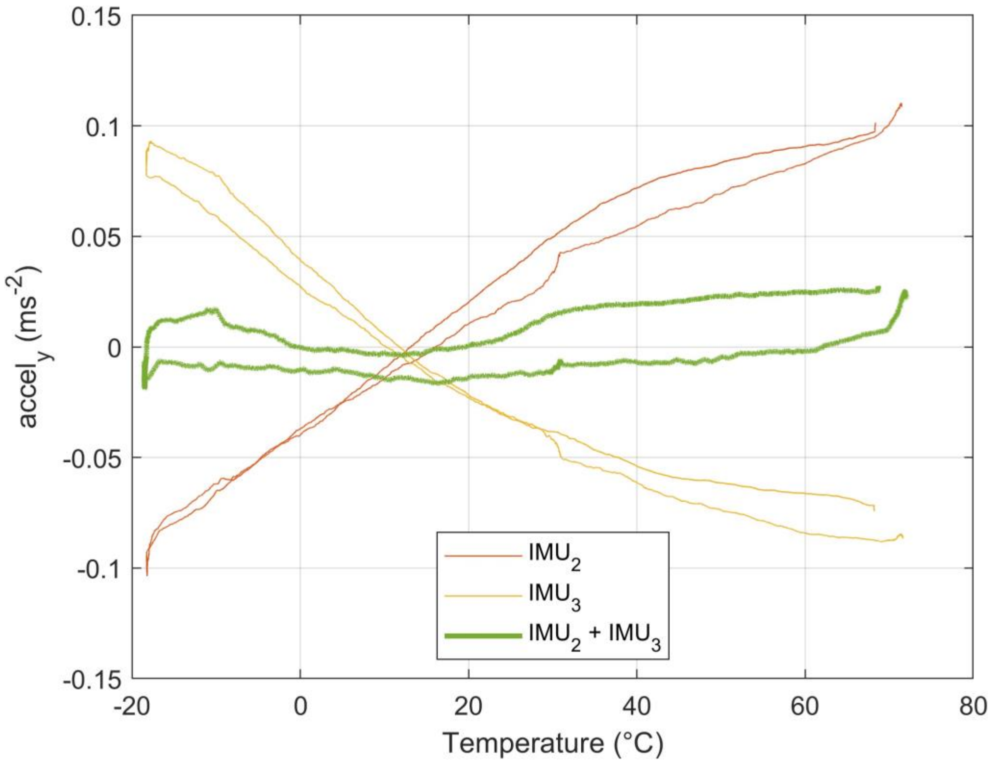
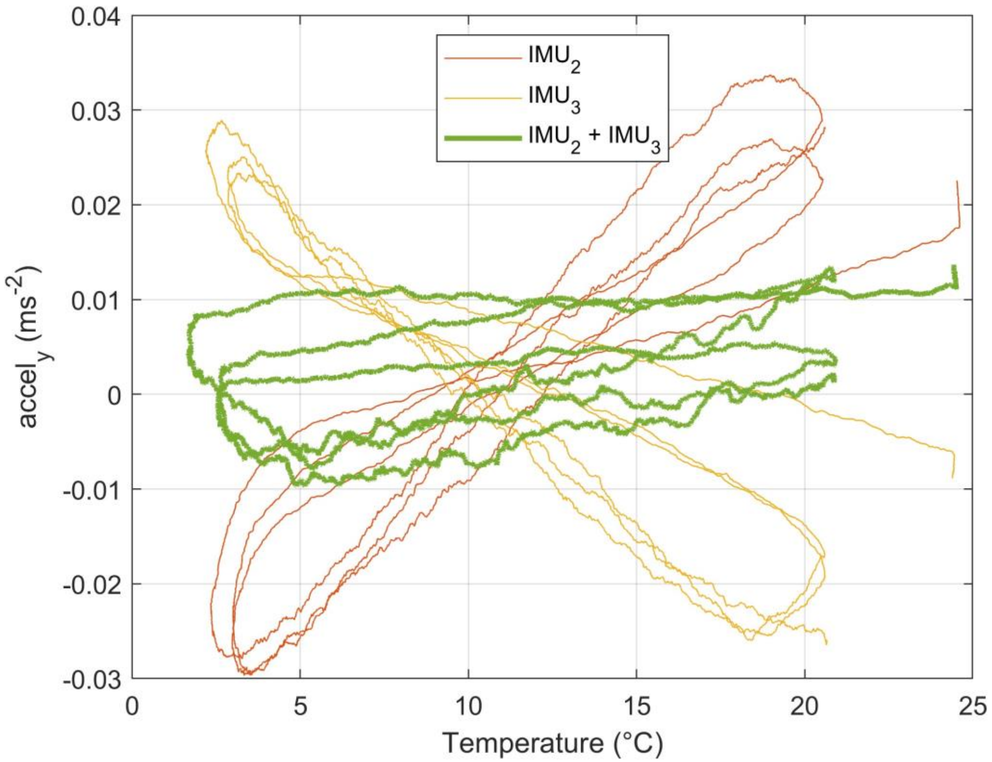


X and y axes of IMUs 2 and 3 have opposing responses. Could their combination help null the error?

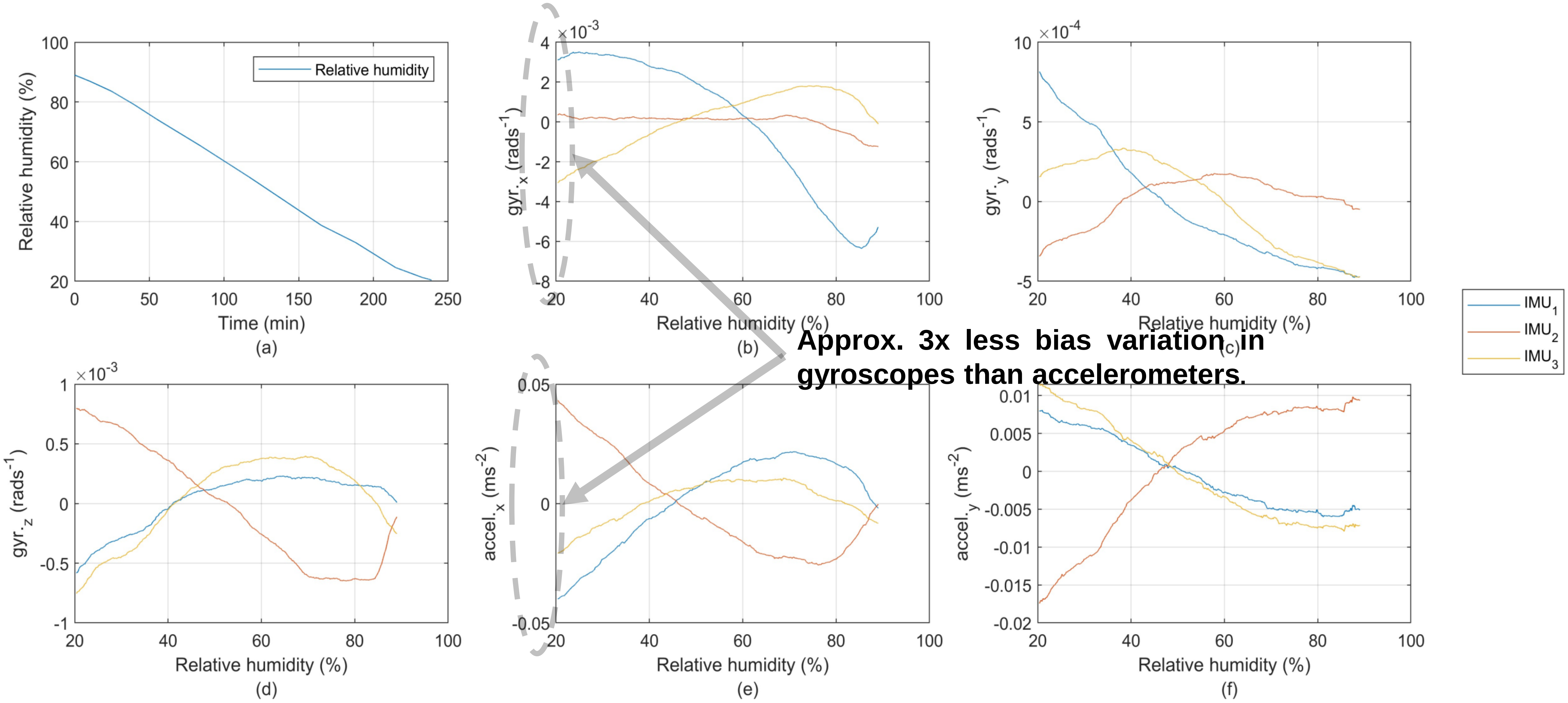
3. Zero Bias Reduction by Fusing Responses





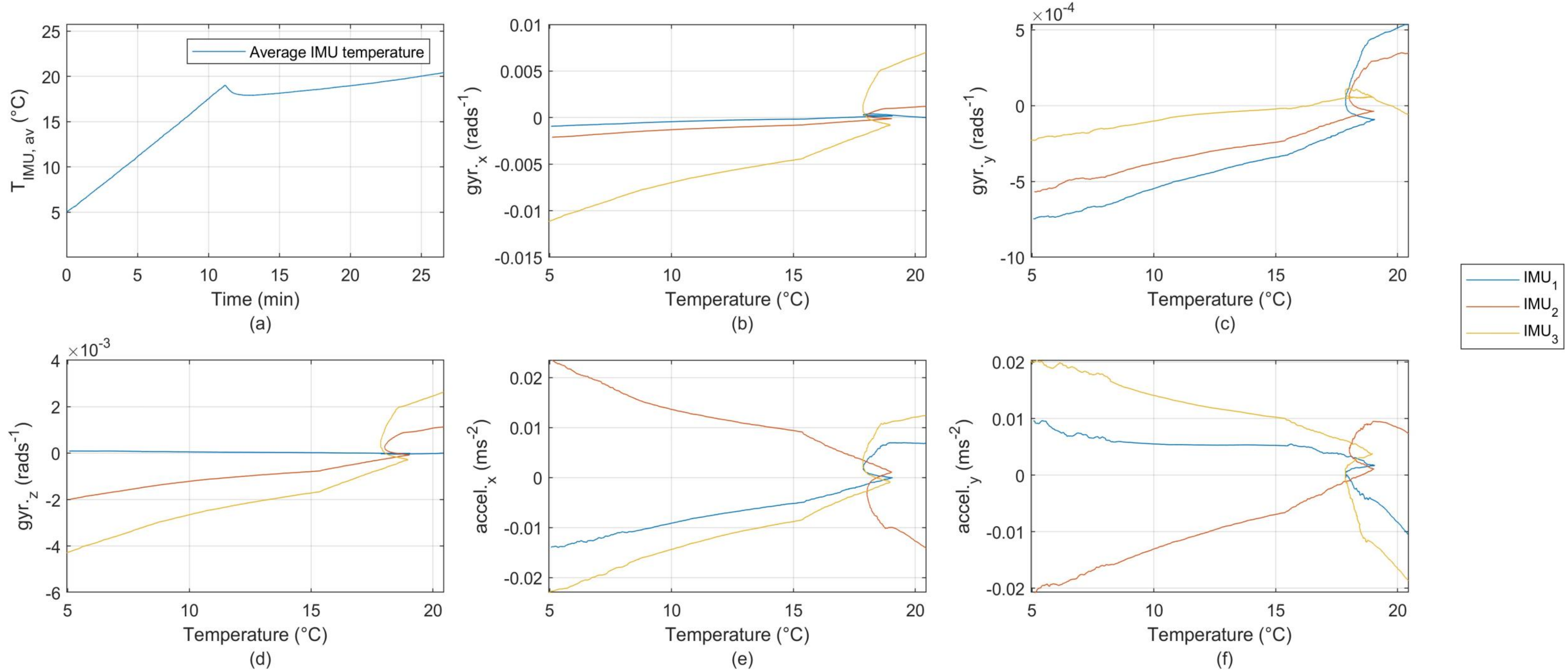
Zero bias reduced by about seven times for the temperature sweep and approximately halved the bias variation for the temperature cycle experiments.

4. IMU Zero Bias Drift with Humidity



Approx. 3x less bias variation in gyroscopes than accelerometers.

5. IMU Bias Variation – Thermal Shock



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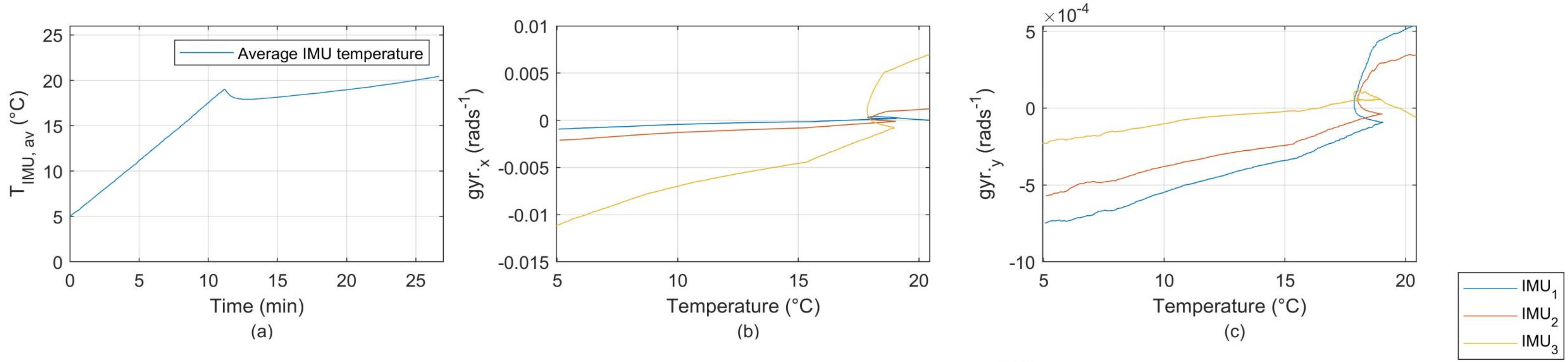
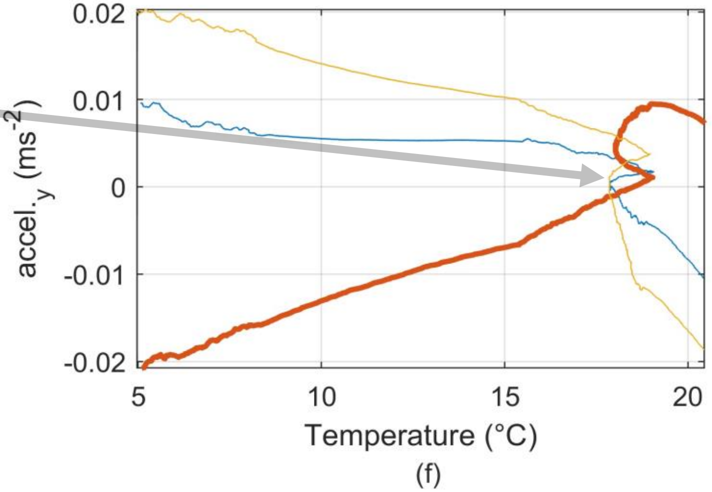
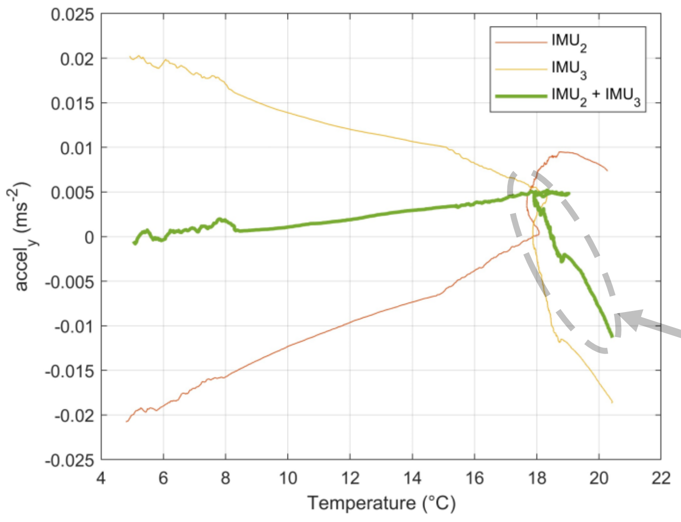


Initially opposing responses become correlated after sudden change in rate of temperature change.

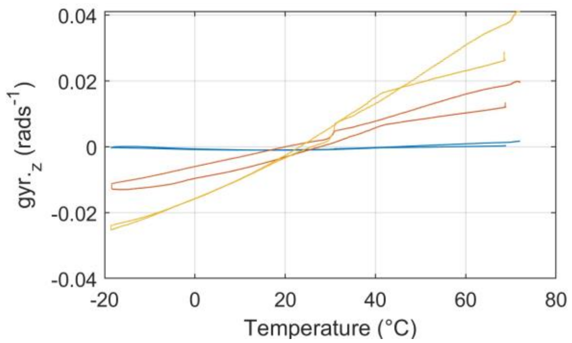


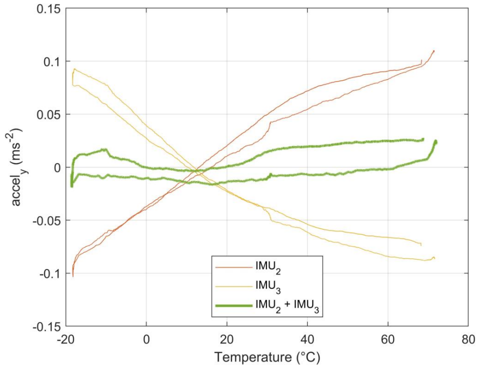


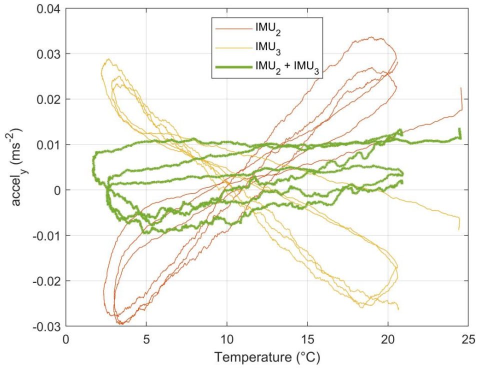
Correlation of responses risks reinforcement of bias error.

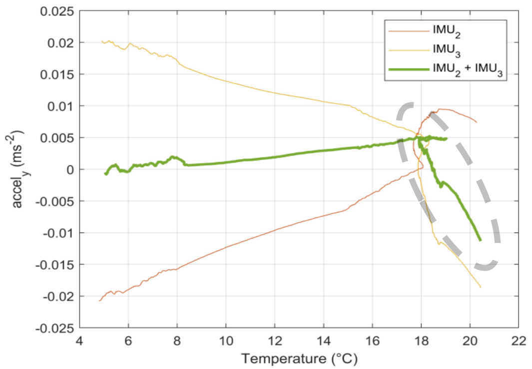
Conclusions

- The sensor-to-sensor temperature bias responses varied approximately 15 times more between gyroscopes than accelerometers.
- Certain accelerometer axes had opposing temperature-bias and humidity-bias responses suggesting their fusion could help reduce the error by as much as sevenfold.
- The accelerometers were affected more (~3x) by humidity than the gyroscopes suggesting they may not be hermetically sealed.
- Sudden changes in the rate of temperature change should be avoided as it may cause opposing responses to become correlated which would reinforce the bias error.









Future Work

- Hermetically seal one of the IMUs and see if the humidity-bias error for the accelerometers is reduced.
- Acquire more low-cost sensors to find more axes with flat temperature-bias responses.
- Fuse sensors with flat and opposing responses to create a higher quality sensor package.