Robotic Ultrasound Assistance

via Hand-Over-Hand Control

Group 5:
Kevin Gilboy

Mentors:
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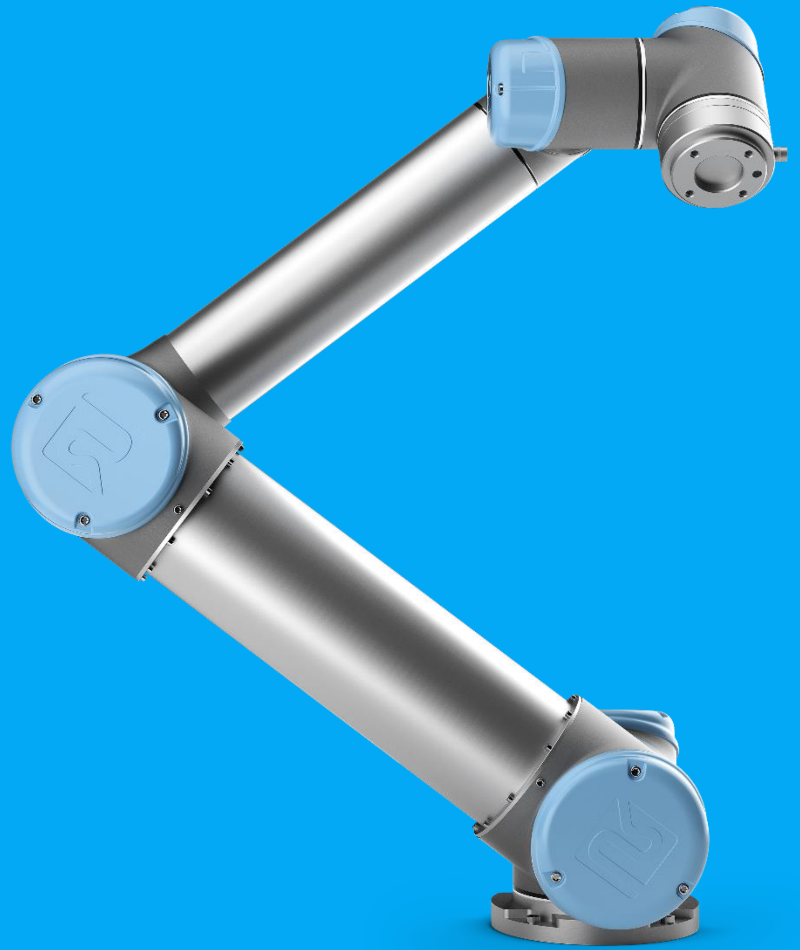
Dr. Mahya Shahbazi



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601.656 CIS2 Spring 2019

Summary

- Problem
  Sonographers commonly develop work-related musculoskeletal issues [1] by holding probe in static, contorted positions and applying large forces [2]
- Goal
  Provide sonographers with a smooth moving, hand-guidable, ultrasound wielding robot to do the strenuous holding for them.
- Status – on target!
  - All activities and deliverables met on time
  - Minimum goal achieved
  - One tweak to future milestone date due to HW upgrade, deliverable untouched
  - One unresolved peripheral dependency

[1] Rousseau, 2013
[2] Schoenfeld, 1999

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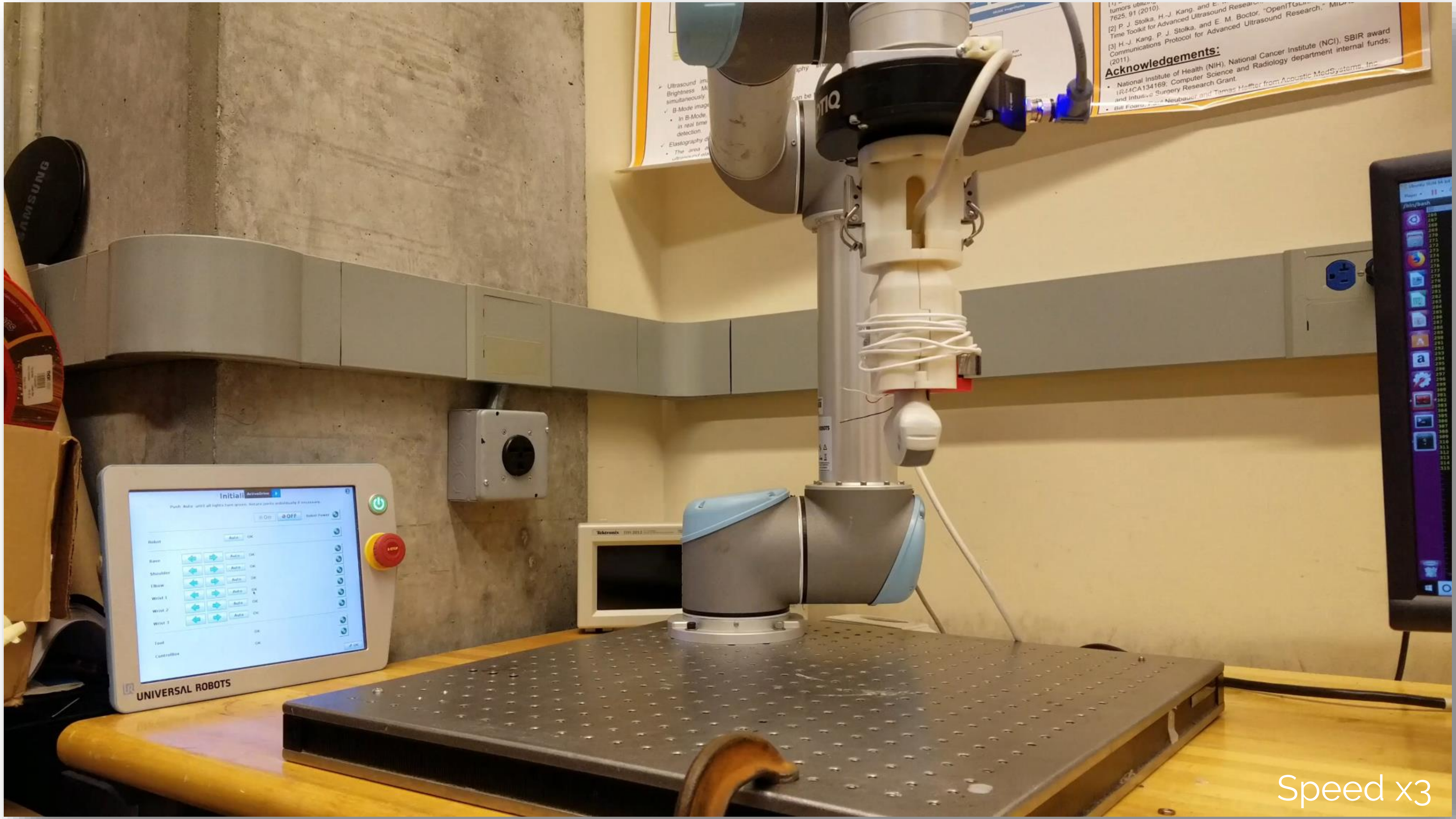
Some Proof of Admittance Control, Gravity Compensation



Updates

Update: Key Activities and Deliverables

	Activity	Deliverable
Min.	C++ interface with robot and dual force sensors to collect data	Datasets for multiple static poses
	Implement rudimentary in-air admittance control, gravity compensation	Video of functionality, graphs showing compensation, code and documentation
Expected	Implement improved admittance control through adaptive Kalman filtering incorporating probe-pt. force feedback	Video of functionality, code and documentation
	Qualitatively & quantitatively evaluate the system with test subjects	Report with graphs and statistical validation
Max.	Virtual fixtures	Video of functionality, code and documentation

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Old

Update: Activity Dates

	Key Activity Milestones	Deliverables
Min.	• 2/4 Sensor interfacing • 2/16 Gravity compensation	• 2/5 Document of static sensor readings for multiple poses • 2/17 Video of in-air HoH control, code & documentation
Expected	• 3/27 Kalman filtering • 4/4 Load cell • 4/26 Sonographer testing	• 4/5 Video of functionality, code & documentation • 5/3 Document of test results
Max.	• 4/26 Virtual fixtures	• 5/3 Video of functionality, code & documentation

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New

Update: Activity Dates

Key Activity Milestones

Min.

- 2/4 Sensor
- 2/16 Gravity

Expected

- ~~3/27~~ 4/4 Kalman filtering
- ~~4/4~~ 3/27 Load cell
- 4/26 Sonographer testing

Max.

- 4/26 Virtua

Deliverables

Min.

- Document of static sensor readings for multiple poses
- 17 V... ntrol, ...tion

Expected

- 4/5 Video of functionality, code & documentation
- 5/3 Document of test results

Max.

- Video of functionality, code & documentation

Would like to spend more time tuning the filter for optimal result

Deliverable date unchanged

HW change to Variense force sensor. Built-in ADC, serial interface. Much easier ☺

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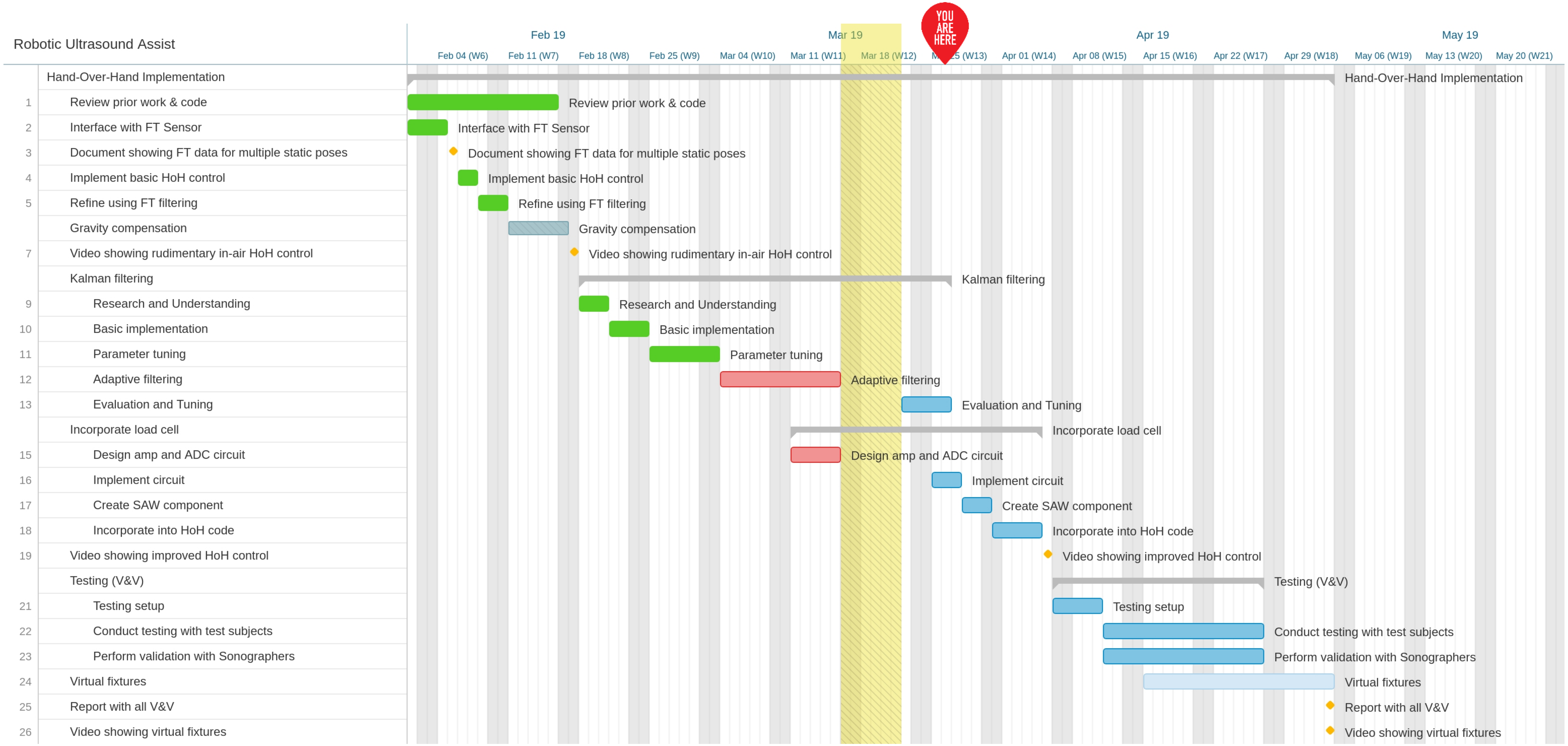
Old

Update: Activity Timeline



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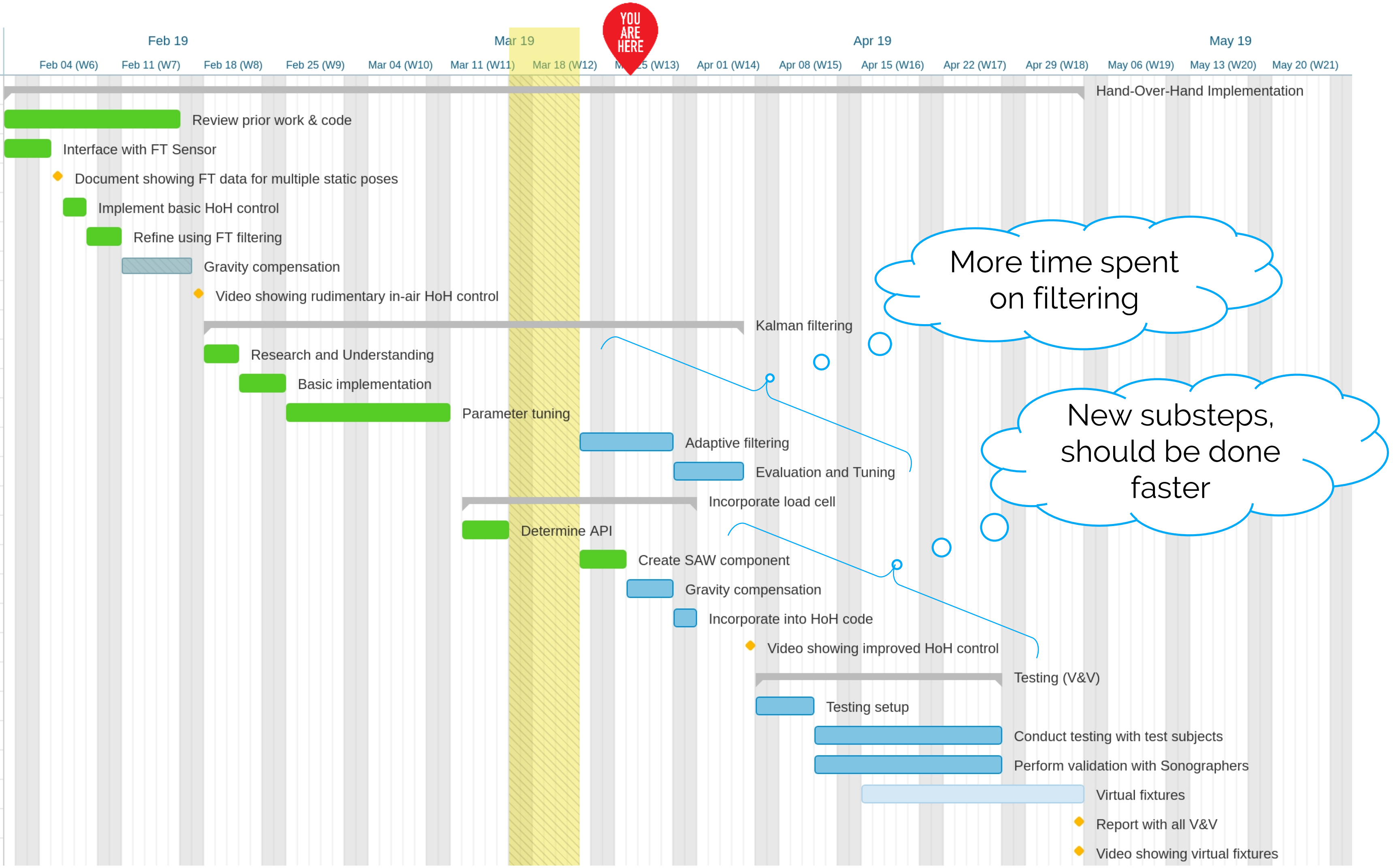
New

Update: Activity Timeline

Robotic Ultrasound Assist

	Hand-Over-Hand Implementation
1	Review prior work & code
2	Interface with FT Sensor
3	Document showing FT data for multiple static poses
4	Implement basic HoH control
5	Refine using FT filtering
	Gravity compensation
7	Video showing rudimentary in-air HoH control
	Kalman filtering
9	Research and Understanding
10	Basic implementation
11	Parameter tuning
12	Adaptive filtering
13	Evaluation and Tuning
	Incorporate load cell
15	Determine API
16	Create SAW component
17	Gravity compensation
18	Incorporate into HoH code
19	Video showing improved HoH control
	Testing (V&V)
21	Testing setup
22	Conduct testing with test subjects
23	Perform validation with Sonographers
24	Virtual fixtures
25	Report with all V&V
26	Video showing virtual fixtures



Update: Dependencies

Dependency	Need	Status	Followup	Contingency Plan	Planned Deadline	Hard Deadline	
Robot	Actuated to provide "power-steering"	Have a working UR5	N/A	If breaks, could seek continued permission to use UR3 in B08	2/1	2/1	✓
6DOF F/T Sensor	Admittance control input	Have a working Robotiq FT-150	N/A	If breaks, approach the CS dept to borrow one of their FT sensors	2/1	2/1	✓
~~Load Cell~~ Contact Force Sensor	Decouples force from probe on pt.	Have a working 3DoF Variense FSE103	N/A	If broken, continue with load cell or without contact force feedback	2/12	2/28	✓
Ultrasound Probe	Key component for realistic testing	Have a linear probe, several others available in our lab pod	N/A	If disappears, seek permission to use another probe available in lab pod	2/1	4/1	✓
sEMG sensor	Used to measure physical exertion while scanning	Looking to acquire through MUSiiC Lab collaborators	Speak with Dr. Boctor	If unable to acquire, testing can still proceed without sEMG data	3/8	4/12	IN PROGRESS
Phantom (non-anatomical)	Something to test the probe on	Acquired	N/A	If disappears, seek permission to use one of the many phantoms present in B08A	2/1	4/1	✓
HIRB ~~Approval~~ First Submission	Testing with subjects	Submitted, trained for human subjects testing, HIPPA	N/A	If not approved in time, we can still perform qualitative validation with sonographers to see if exertion is improved in their expert opinion.	2/22	3/1	✓
HIRB Approval	Testing with subjects	Received brief feedback, crafted an update	Resubmitting today (3/26)	If not approved in time, we can still perform qualitative validation with sonographers to see if exertion is improved in their expert opinion.	3/29	4/12	IN PROGRESS

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Original 3/15 deadline was for ordering an sEMG system. Now we look to find one at JHMI instead

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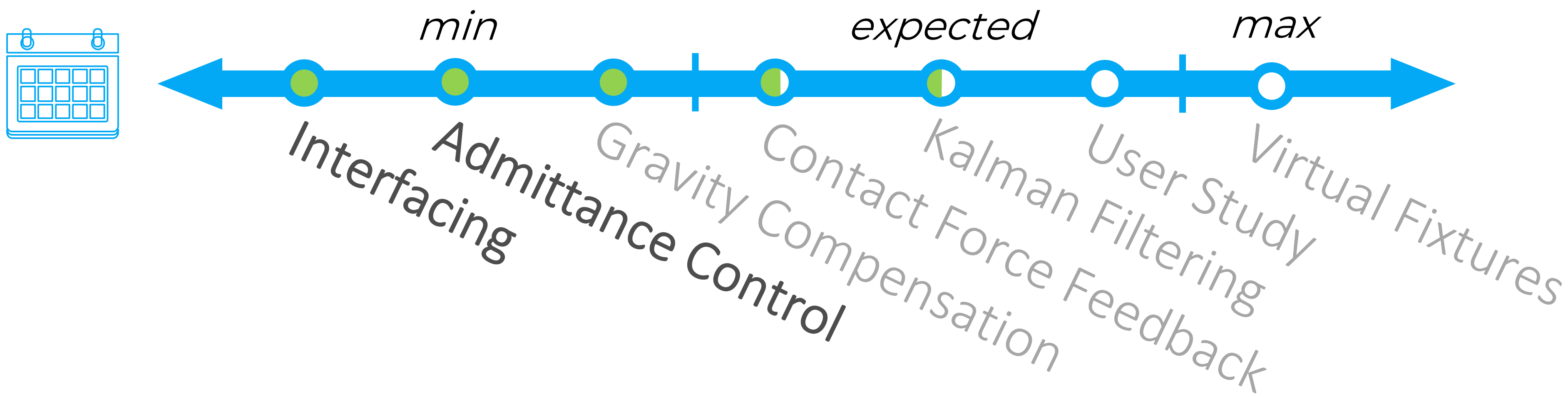
Work To Date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Interfacing
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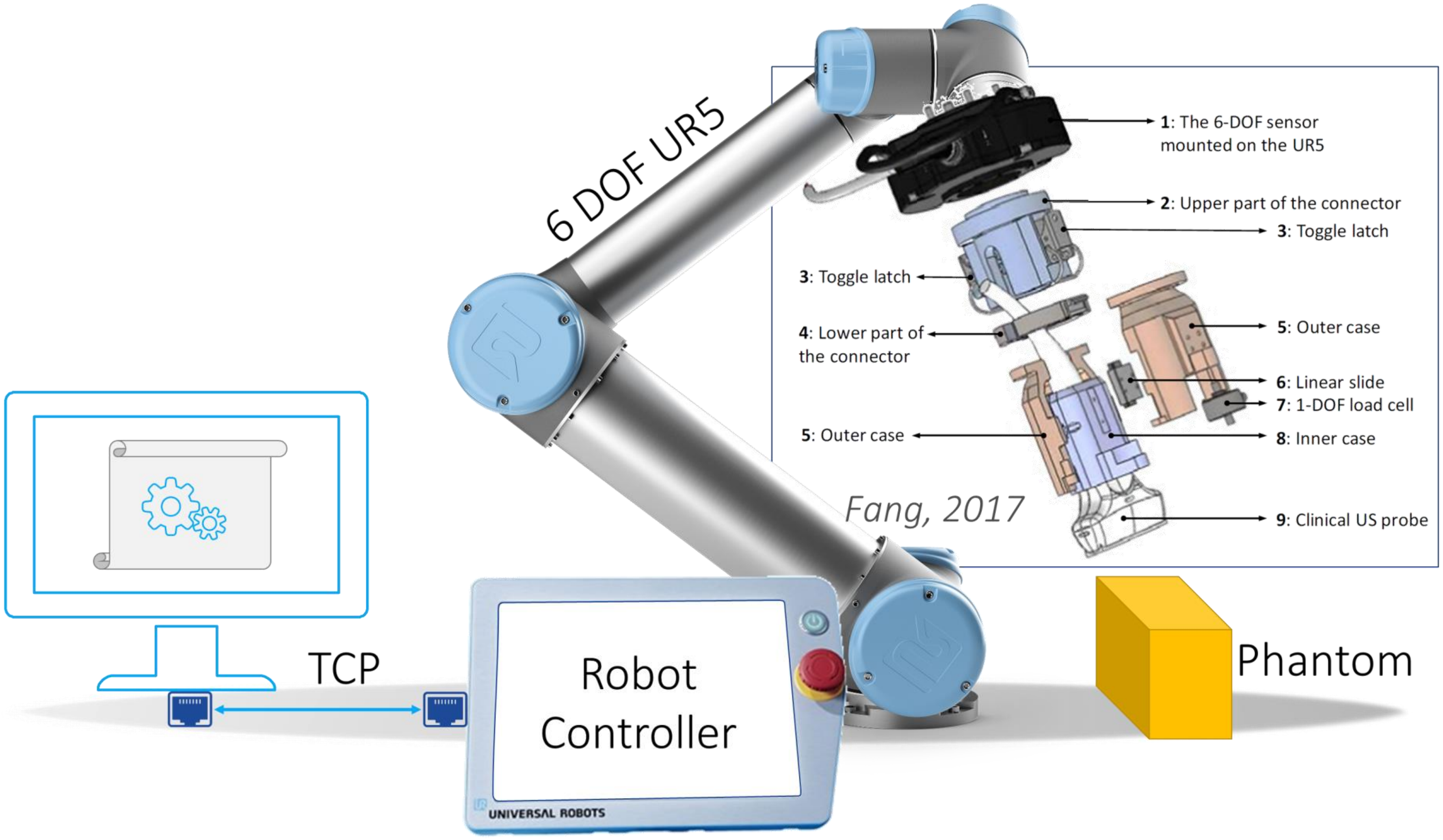
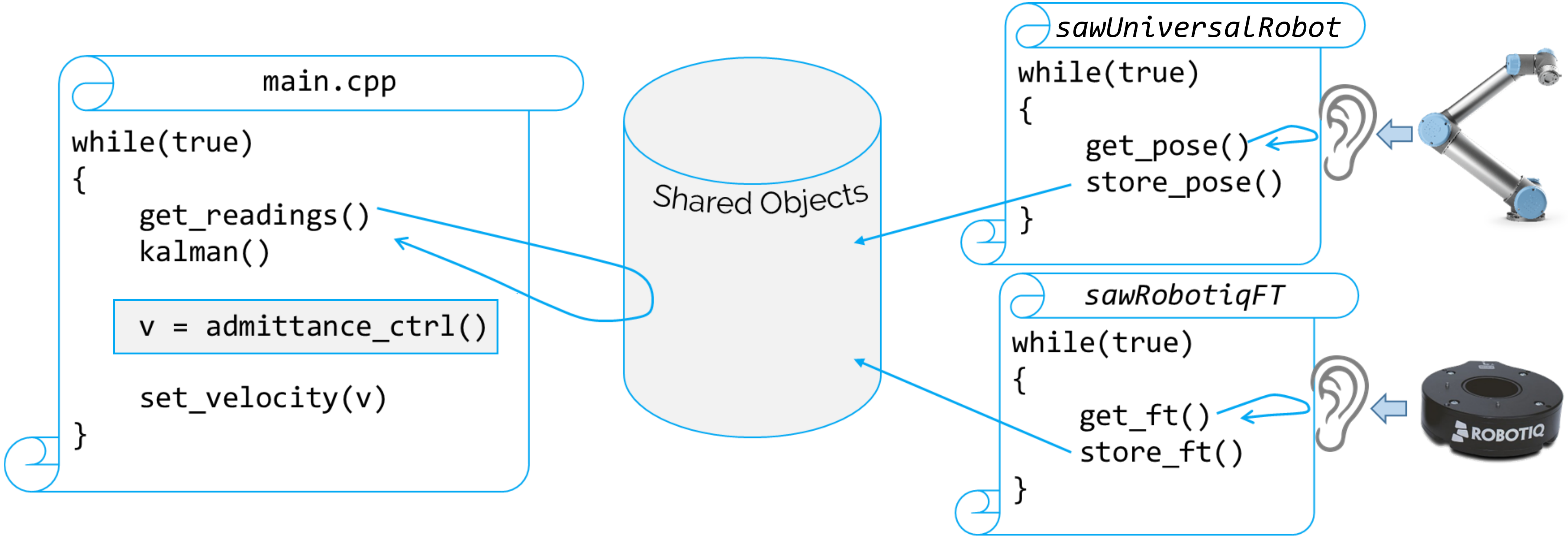
Interfacing and Admittance Control



Interfacing and Admittance Control

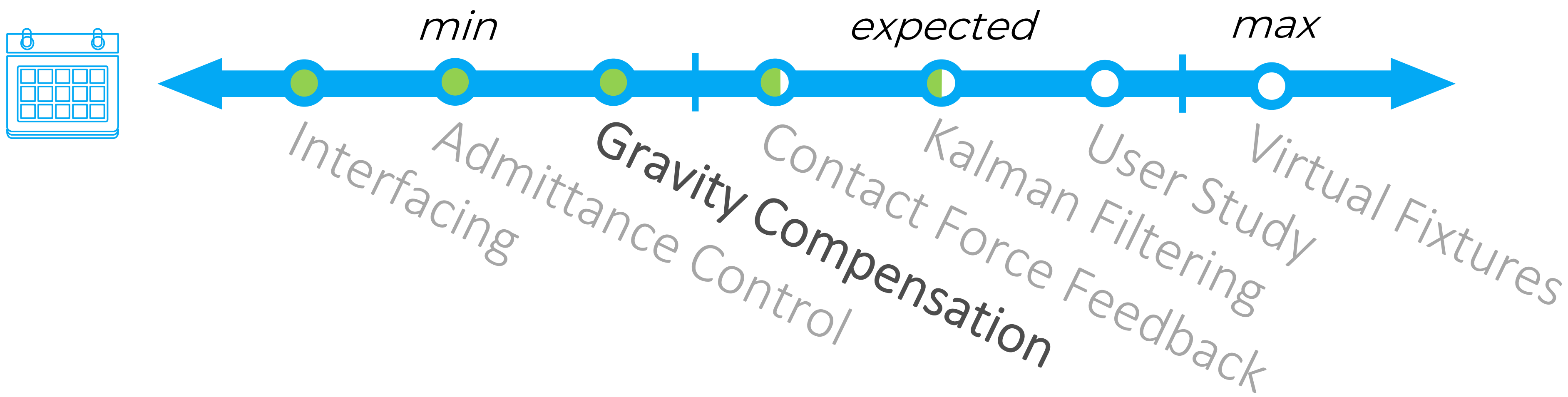


Admittance control inspired by Finnochi, 2016

$$force2linvel(f) = (|f| < 0.1)\ ?\ 0\ :\ 0.325\, e^{1-\left(\frac{25}{|f|}\right)} * sgn(f)$$

$$torque2rotvel(\tau) = (|\tau| < 0.1)\ ?\ 0\ :\ 0.125\, e^{1-\left(\frac{5}{|\tau|}\right)} * sgn(\tau)$$

Work To Date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Gravity Compensation – Method

Automated data collection script of 32 static poses
Averaged 736 samples per pose

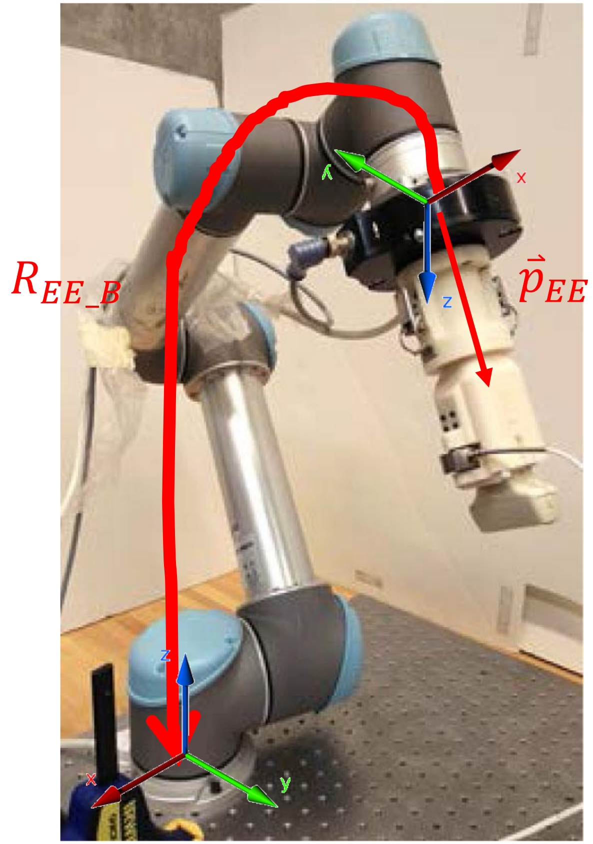
Used least squares to solve for *mg*

$$mg = 4.7740N$$

Using this *mg*, used least squares to solve for p_{EE}

$$\vec{p}_{EE} = [-0.0132, 0]\, m$$

Makes sense due to -x offset of load cell

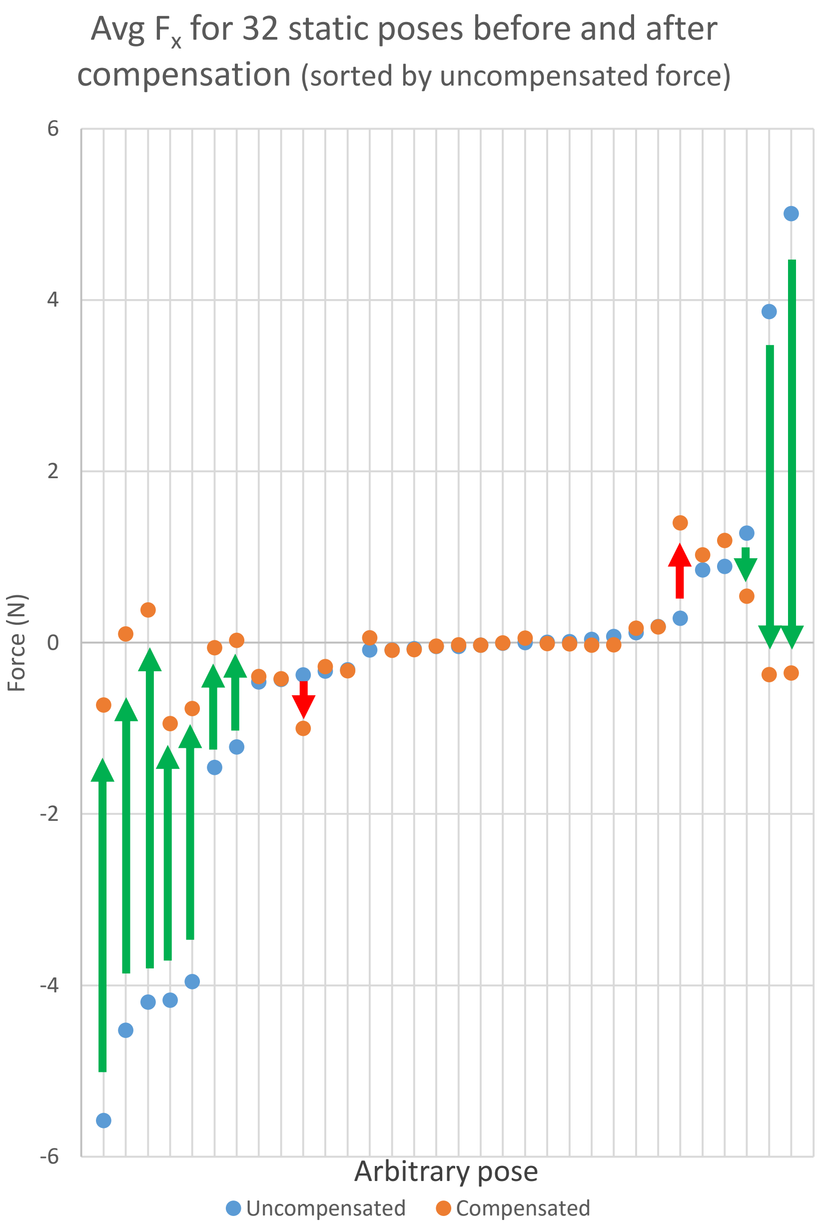


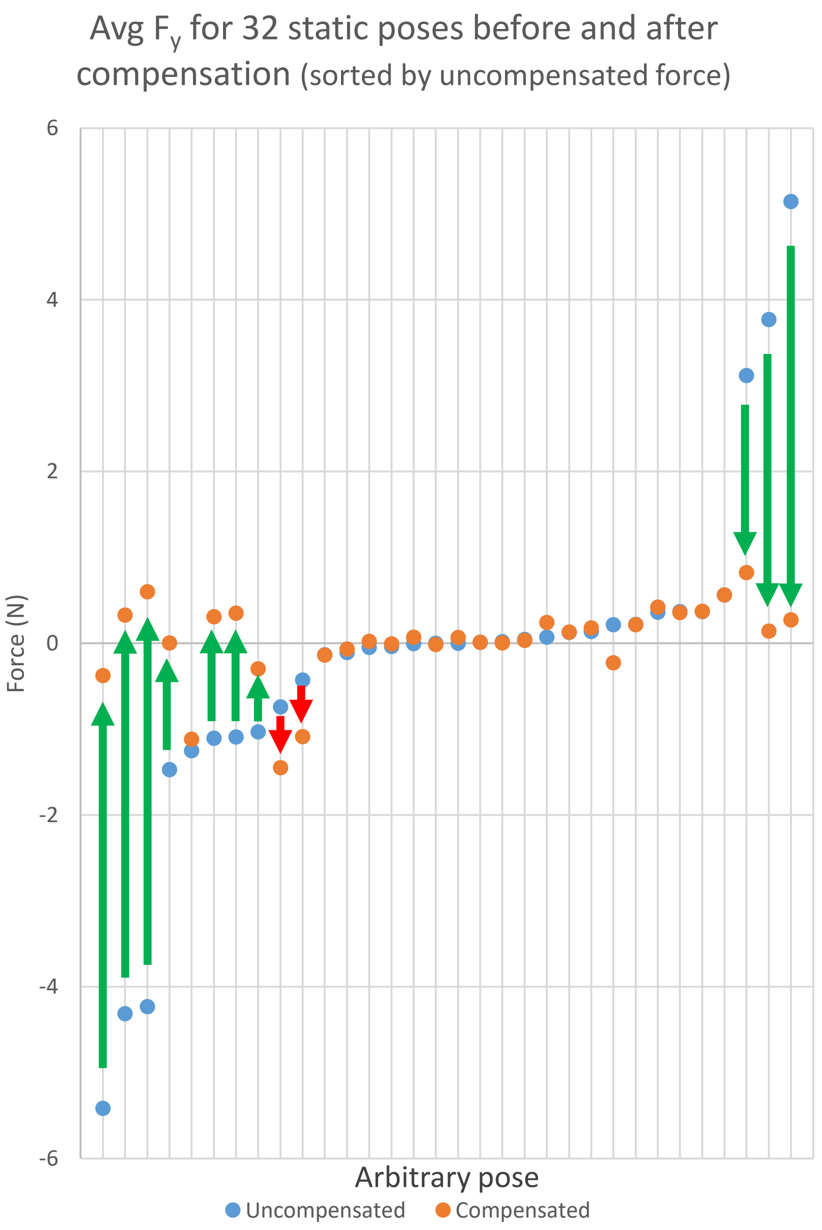
Modified from Fang, 2017

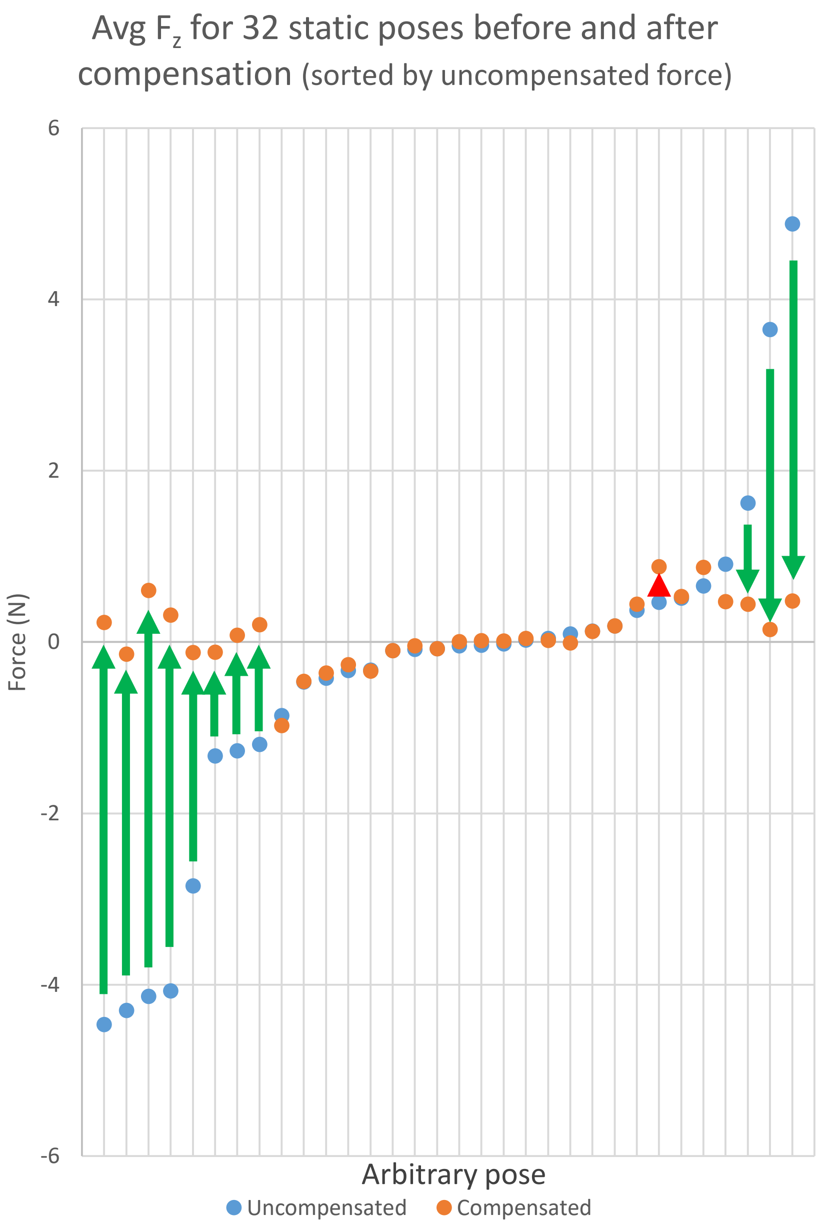
$$\begin{bmatrix} F \\ T \end{bmatrix}_{hand} = \begin{bmatrix} F \\ T \end{bmatrix}_{ext} - \left(\begin{bmatrix} R_{EE_B} & 0 \\ -R_{EE_B} * sk(\vec{p}_{COM}) & R_{EE_B} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ -mg \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -mg \\ 0 \\ 0 \\ 0 \end{bmatrix} \right)$$

Due to rebiasing at start

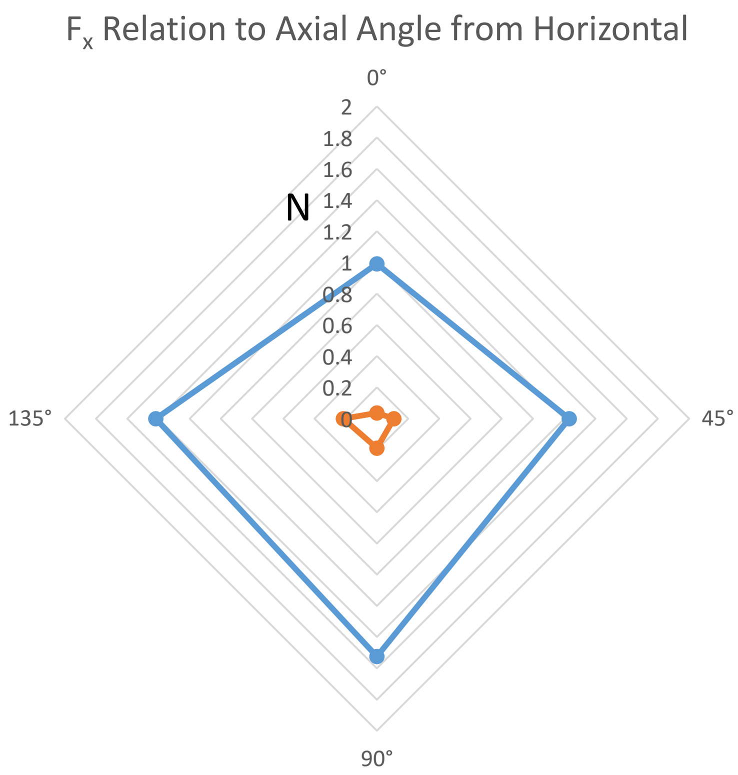
Gravity Compensation – Result for XYZ Forces by Pose



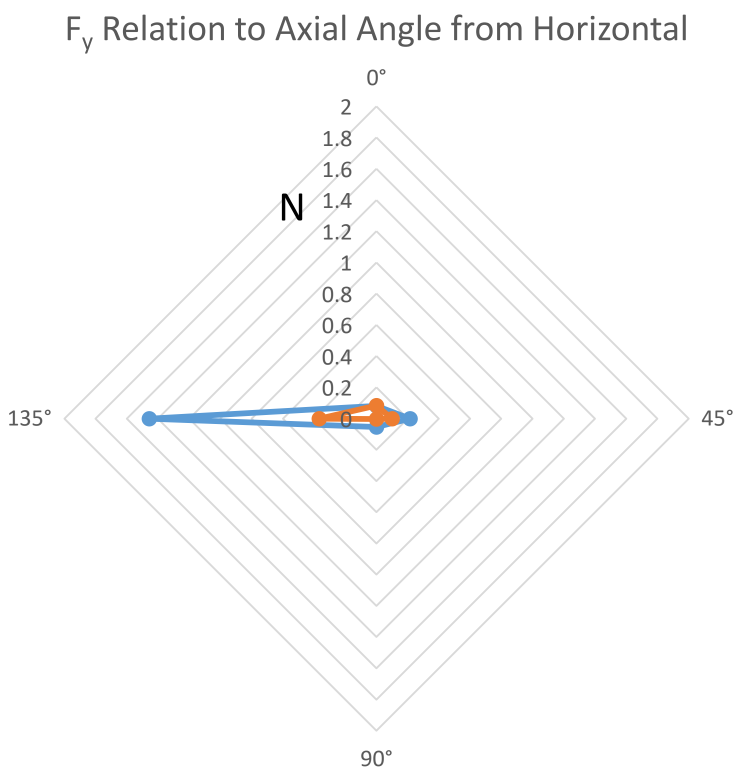




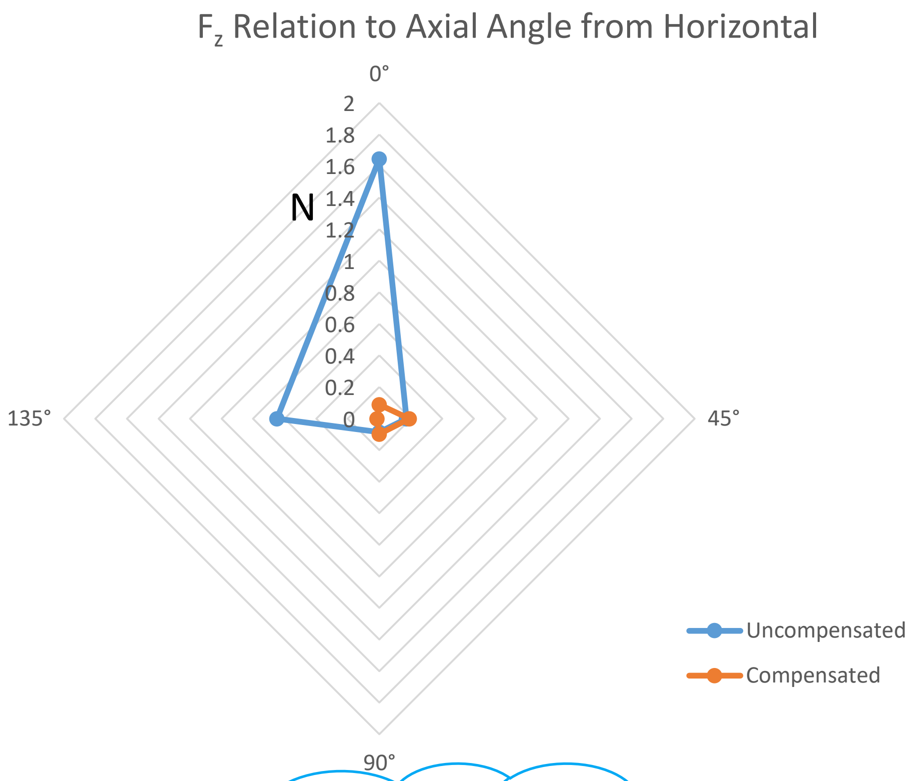
Gravity Compensation – Result for XYZ Forces by Angle



Least accurate when **vertical**. Likely **due to rebiasing in horizontal direction**

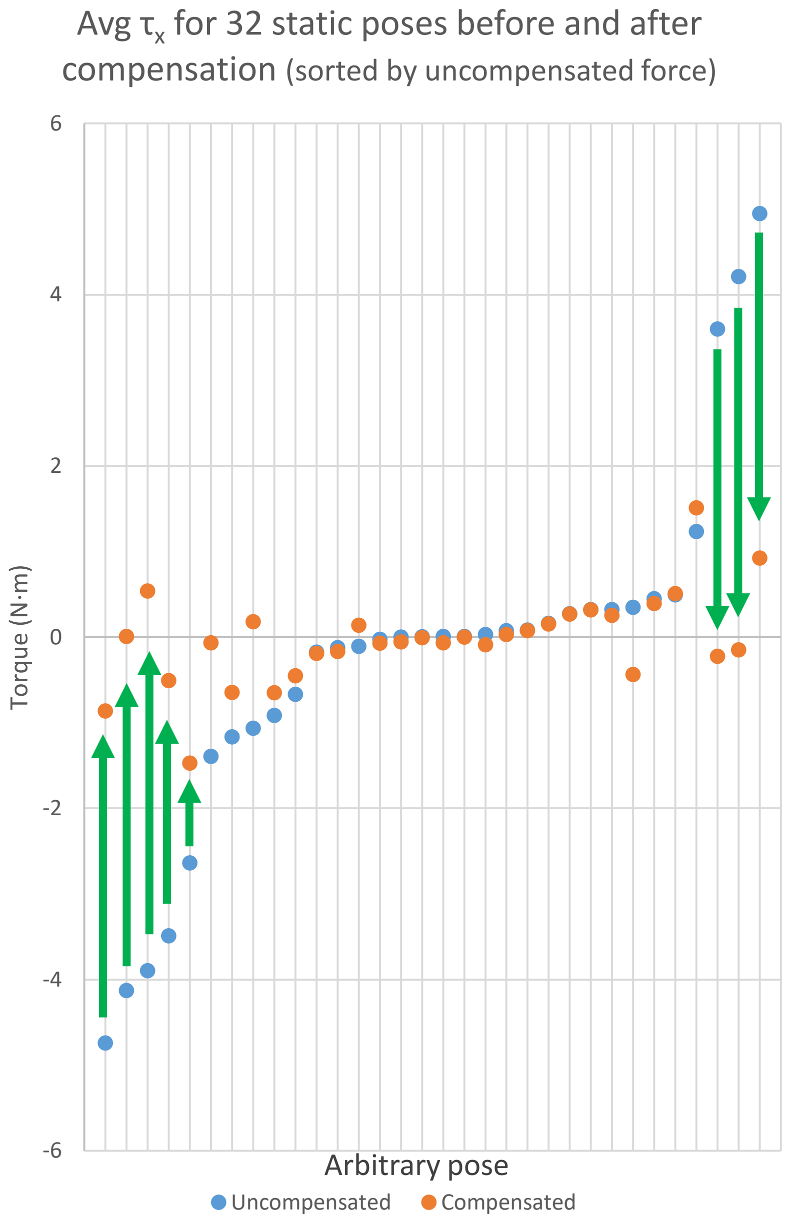


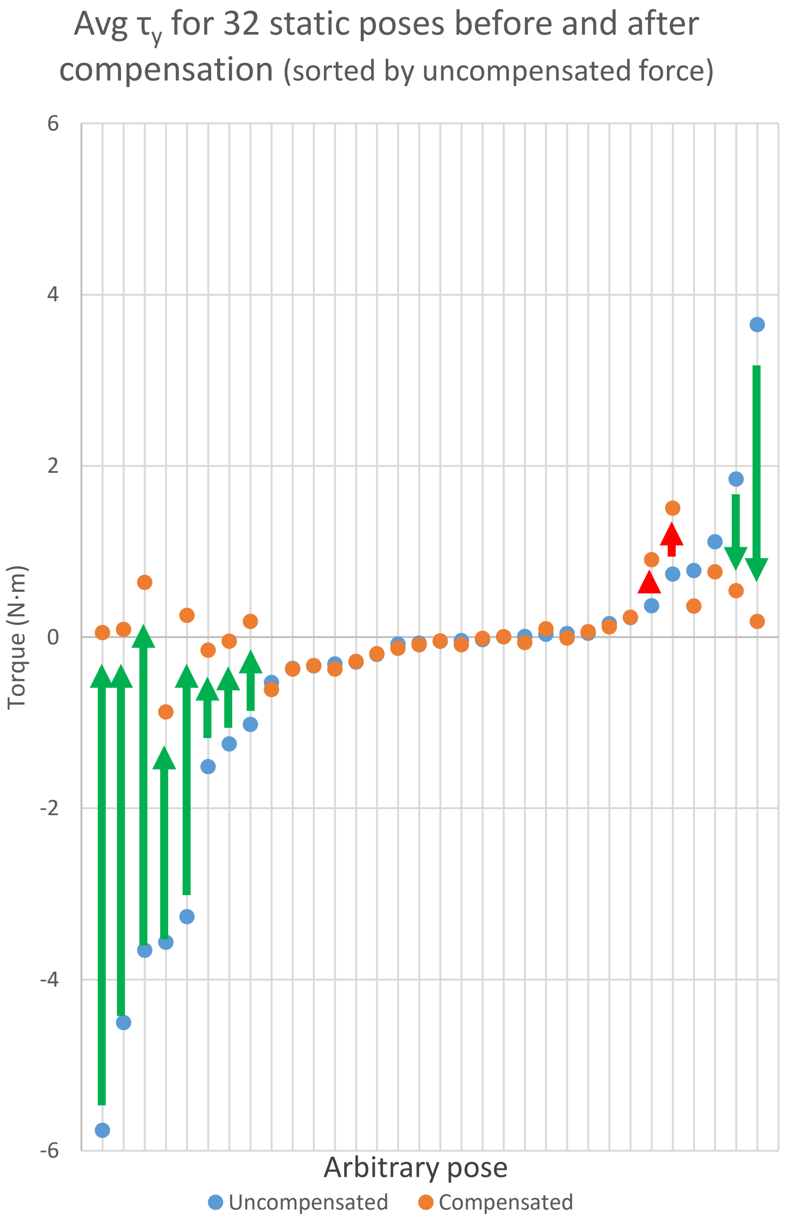
Least accurate for 135˚ from horizontal, likely **due to load cell offset**

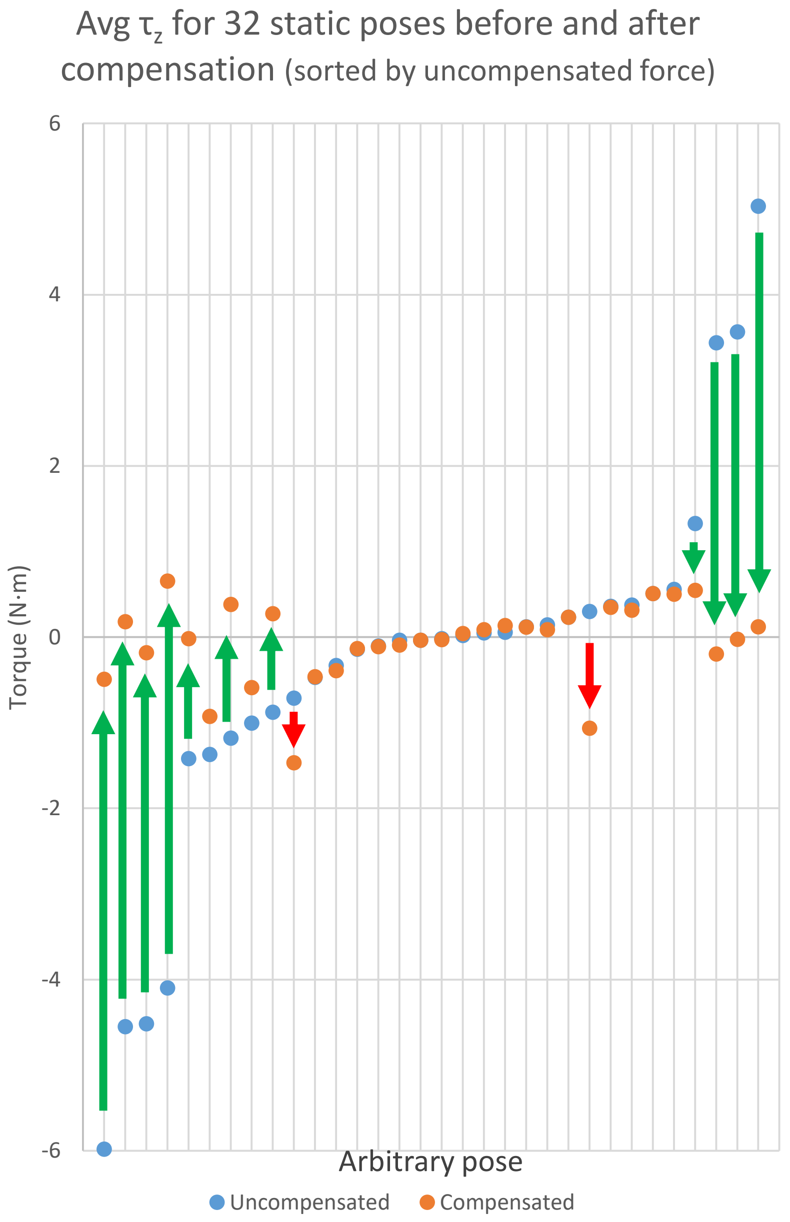


Least accurate when horizontal, most accurate when vertical. Likely **due to rebiasing in vertical direction**

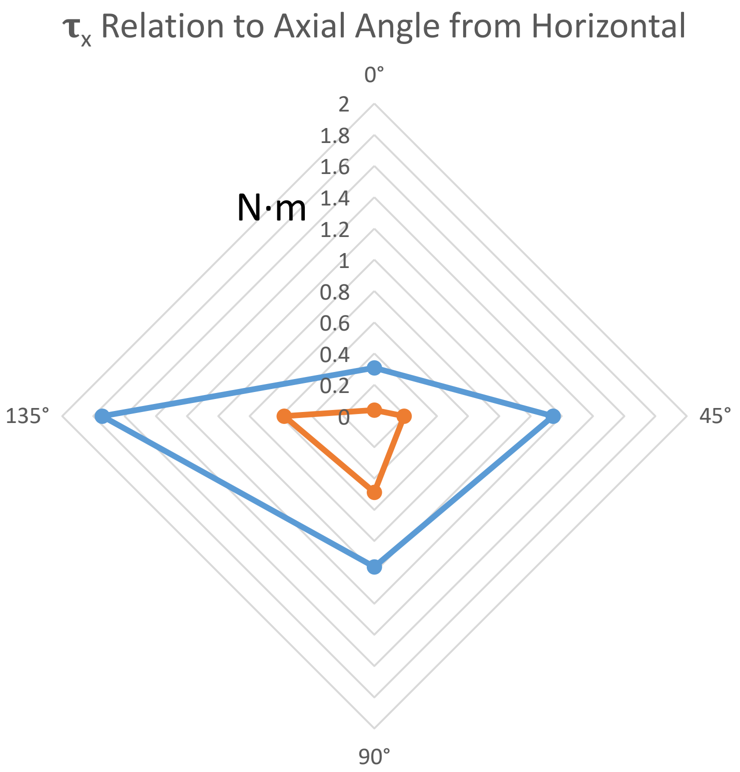
Gravity Compensation – Result for XYZ Torques



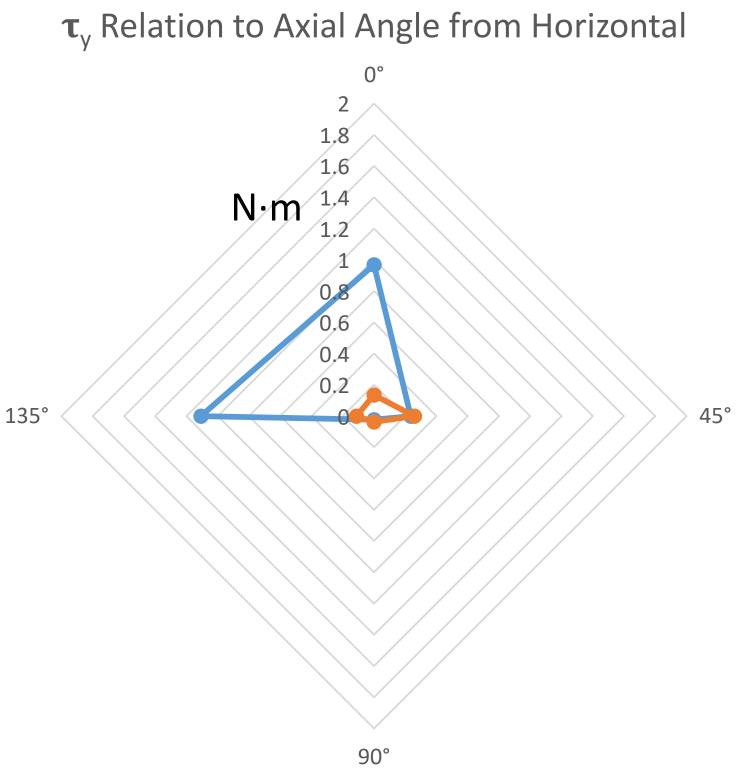




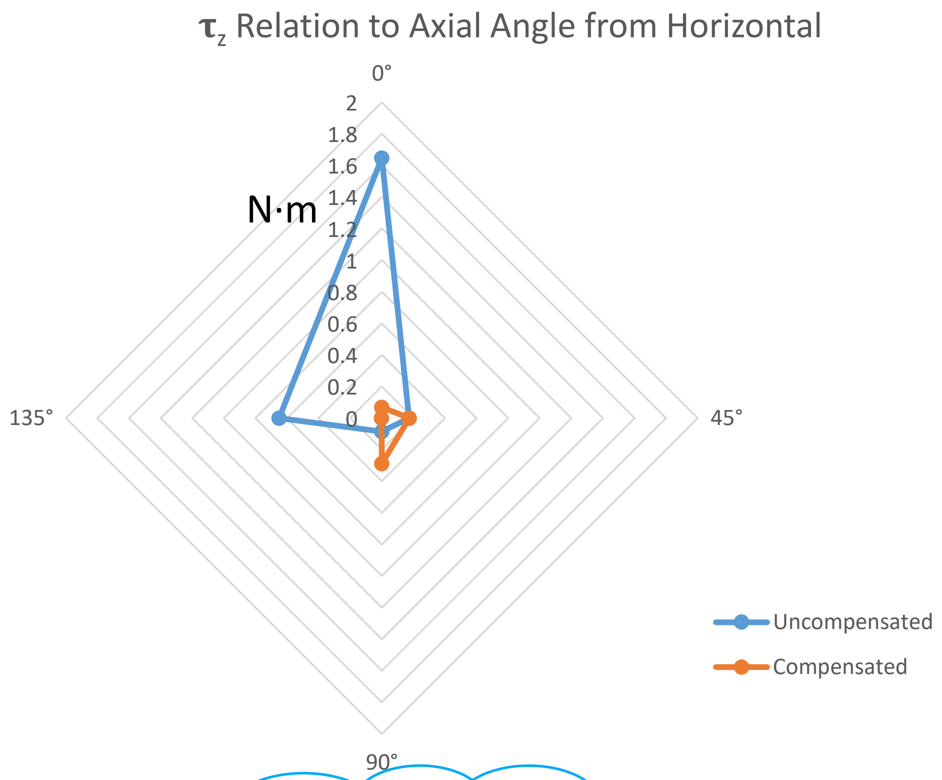
Gravity Compensation – Result for XYZ Torques by Angle



Least accurate when **vertical**. Likely **due to rebiasing in horizontal direction**

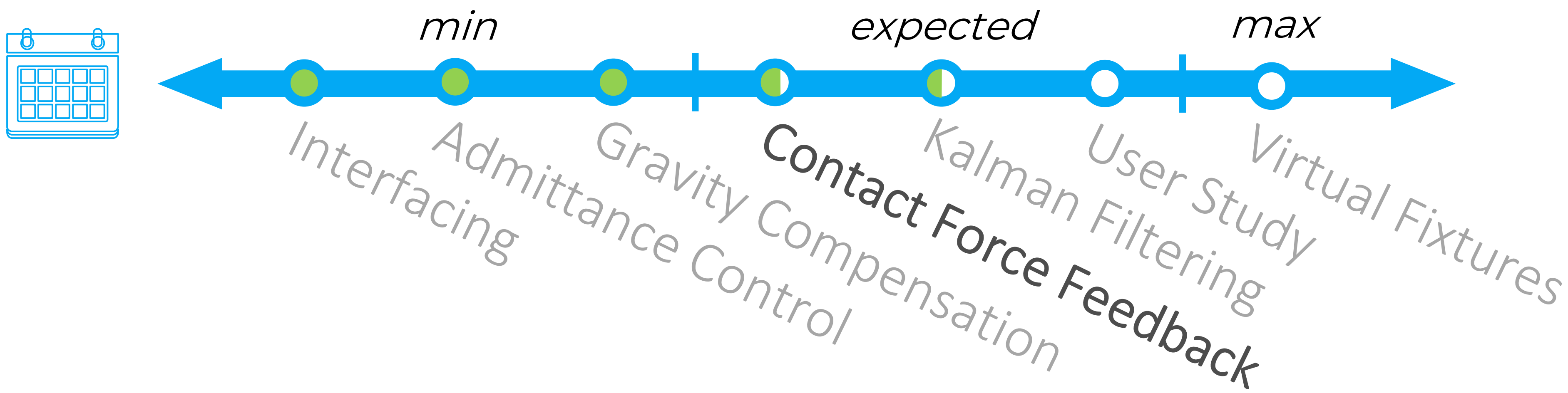


Least accurate for 135° from horizontal, likely **due to load cell offset**



Least accurate when **horizontal**, most accurate when vertical. Likely **due to rebiasing in vertical direction**

Work To Date



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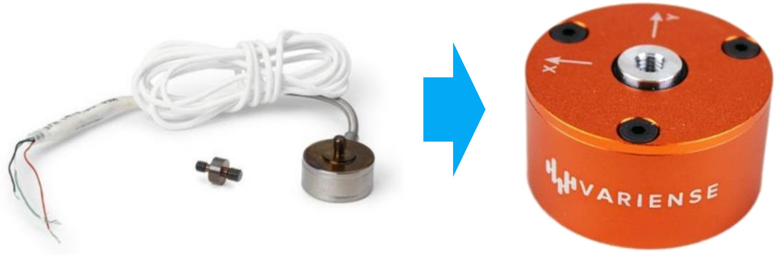
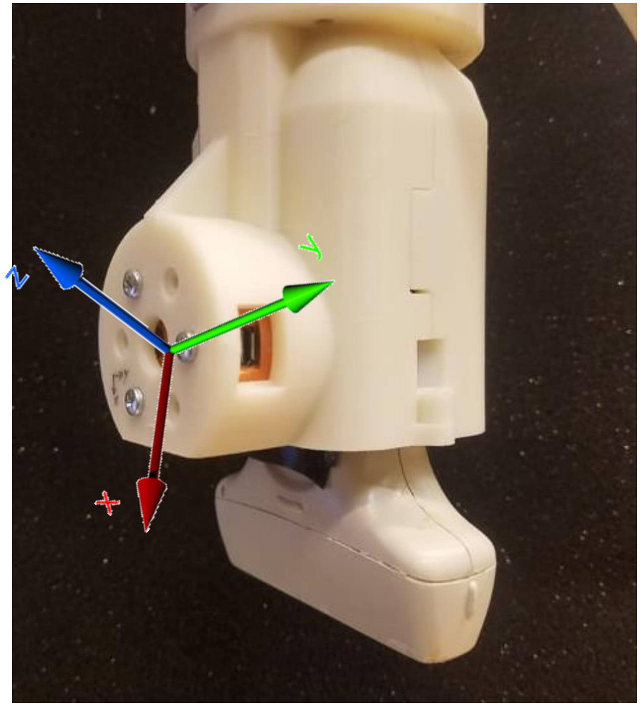
Contact Force Feedback - Decision

Switching from 1DoF load cell to 3DoF axial force sensor





Pros:

- 3 DoF > 1 DoF
- Built-in ADC, amp, serial; no need for PCB
- 80N, 80N, 100N XYZ sensing range
- Sleek housing already built

Cons:

- Housing is “sticky”
- < 1.5N of noise

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Contact Force Feedback - Progress

Documented API is all wrong

Name	Format	Length	Value
Start of message	Char	1 byte	0x0D
~~Size of message~~	~~Char~~	~~1 byte~~	~~0x14~~
~~Type of message~~	~~Char~~	~~1 byte~~	~~0x66~~
Timestamps[1]	Uint32	4 bytes	(MSB) (LSB)
Force X	Float	4 bytes	(MSB) (LSB)
Force Y	Float	4 bytes	(MSB) (LSB)
Force Z	Float	4 bytes	(MSB) (LSB)
End of message	Char	1 byte	0xFF

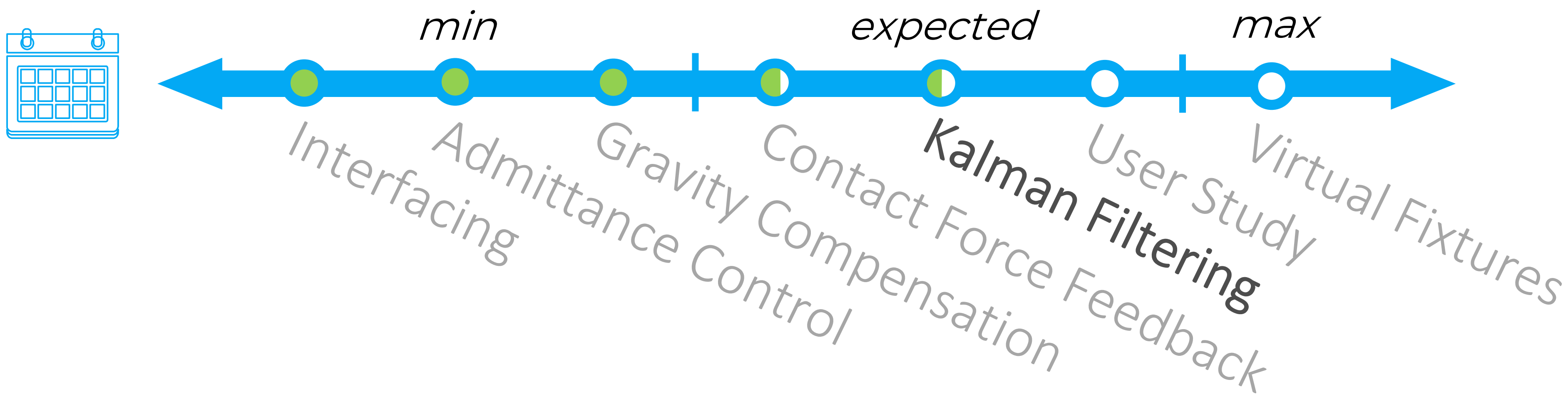
Progress:

- Identified correct API
- Created `sawVarienseFSensor` component to read data over serial at 50Hz

Up Next:

- Determine tool weight contribution via gravity compensation procedure
- Use Kalman filtering to smooth, infer values up to 125Hz
- Perform contact compensation by subtracting from the 6DoF F/T

Work To Date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Kalman Filtering – First Implementation

Performed on **linear velocities** after sigmoidal transformation of F/T→V
Constant acceleration model (a=1.8)

Static, non-adaptive covariances R, Q (to start)
State transition matrix uses dt=0.01s (100Hz)

Parameters:

- Measurement vector **m** ∈ R^{6x1}
  - For us is $[V_x, V_y, V_z, 1.8, 1.8, 1.8]$
- Sensor noise/confidence **R** ∈ R^{6x6}
- Action uncertainty **Q** ∈ R^{6x6}
- Measurement picker **H** = eye(6)
- Transition matrix **A** ∈ R^{6x6} for given dt
- Persistent state estimate **X** ∈ R^{6x1}

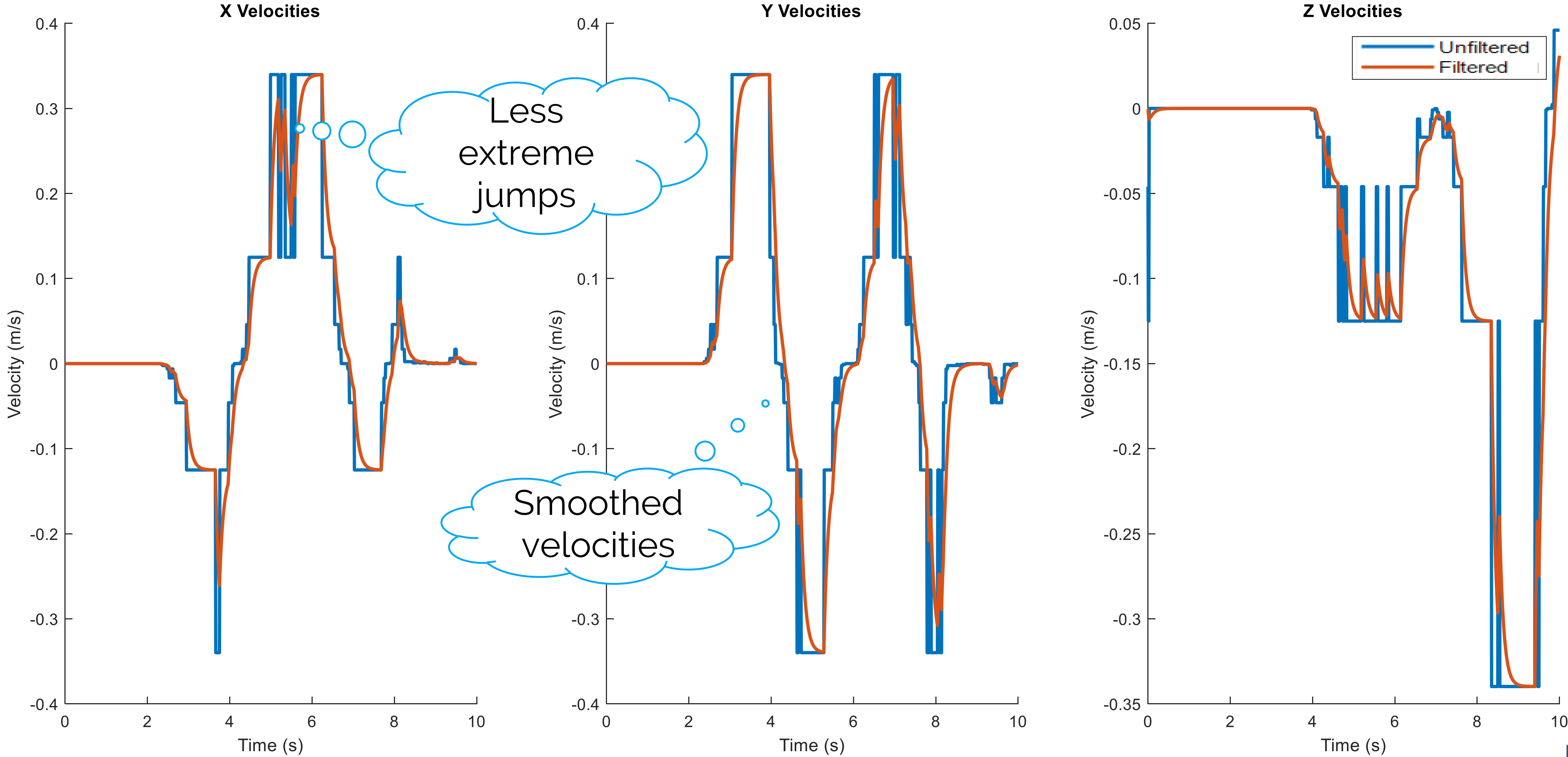
Prediction

$x[t] = Ax[t-1]$	State estimate
$P = (APA^T) + Q$	Predicted error cov

Update

$S = HPH^T + R$	Pre-fit residual cov
$K = PH^T S^{-1}$	Optimal gain
$y = m - Hx[t]$	Pre-fit residual
$x[t] = x[t] + Ky$	Updated state estimate
$P = (I - KH)P$	Update estimate cov

Kalman Filtering – First Implementation Result



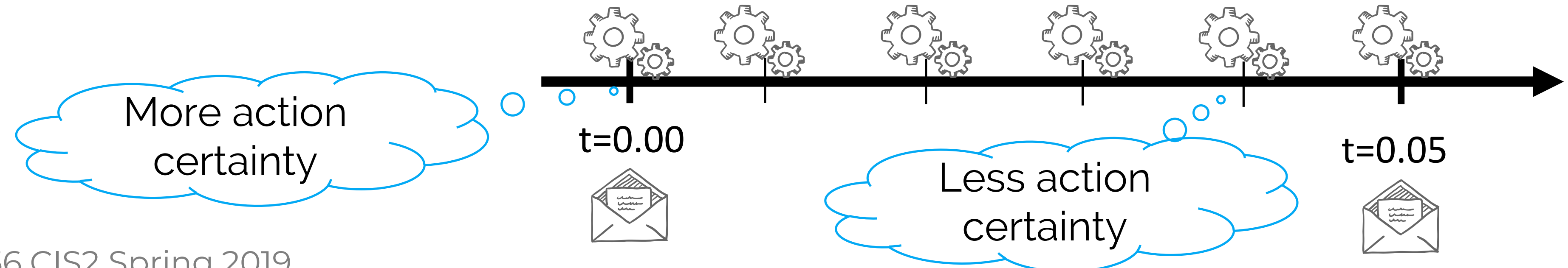
Kalman Filtering – Progress

Progress:

- Working Kalman filter that produces noticeable results on linear velocities
- Tuning by running/comparing parallel filters with different cov matrices

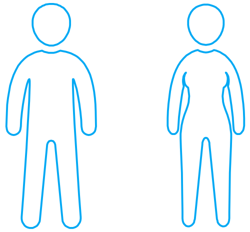
Up Next:

- Filter the F/T before conversion to velocities
- Implement Kalman model in MATLAB, tune covs in simulation
- Adaptive, dynamic covariances
    - Adaptive: Change cov based on post-fit residual
    - Dynamic: Scale cov based on dt since last ground truth (below)



Moving Forward

Approaching the Expected Goal

	Contact Force Compensation	Kalman Filtering	User Study
Problems	• Improve the housing to make it less axially “sticky”		• Continue search for sEMG device 
Steps	• Calculate/implement contact sensor tool weight compensation • Incorporate contact force compensation into admittance control	• Implement in MATLAB • Determine optimal dynamic/adaptive covs for: o Hand forces o Hand torques o Probe forces	• Resubmit HIRB forms • Perform the user study 

References

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A. Schoenfeld, J. Goverman, D. Weiss and I. Meizner, "Transducer user syndrome: an occupational hazard of the ultrasonographer", *European Journal of Ultrasound*, vol. 10, no. 1, pp. 41-45, 1999. Available: 10.1016/s0929-8266(99)00031-2.

R. Finocchi, "Co-robotic ultrasound imaging: a cooperative force control approach", The Johns Hopkins University, 2016.

T. Fang, H. Zhang, R. Finocchi, R. Taylor and E. Boctor, "Force-assisted ultrasound imaging system through dual force sensing and admittance robot control", *International Journal of Computer Assisted Radiology and Surgery*, vol. 12, no. 6, pp. 983-991, 2017. Available: 10.1007/s11548-017-1566-9.

Image References

Title
https://www.universal-robots.com (UR5)

Updates
https://en.wikipedia.org (Green Check)
http://www.sclance.com (In Progress)
https://peoplepng.com (You Are Here)

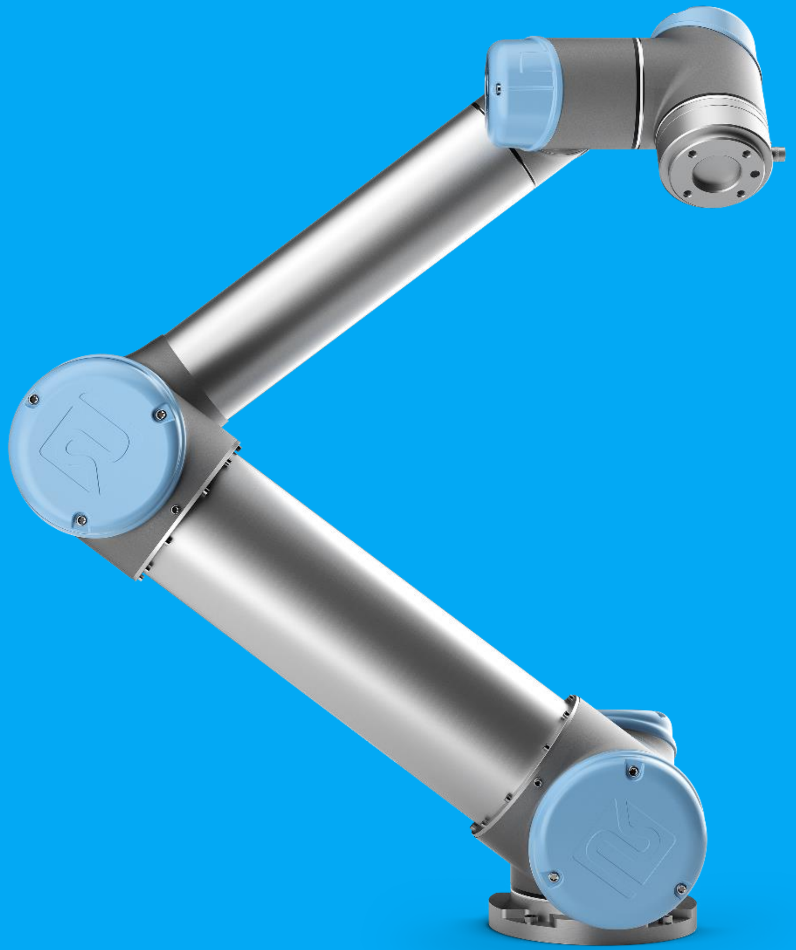
Gravity Compensation
https://english.stackexchange.com (3 axes)
T. Fang, H. Zhang, R. Finocchi, R. Taylor and E. Boctor, "Force-assisted ultrasound imaging system through dual force sensing and admittance robot control", International Journal of Computer Assisted Radiology and Surgery, vol. 12, no. 6, pp. 983-991, 2017. Available: 10.1007/s11548-017-1566-9.

Contact Force Feedback – Decision
http://sine.ni.com (Honeywell sensor)
https://variense.com (Variense sensor)
https://english.stackexchange.com (3 axes)

Approaching the Expected Goal
https://thenounproject.com (bicep)
https://www.onlinewebfonts.com (sEMG line)

Thank you!

Questions?



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