

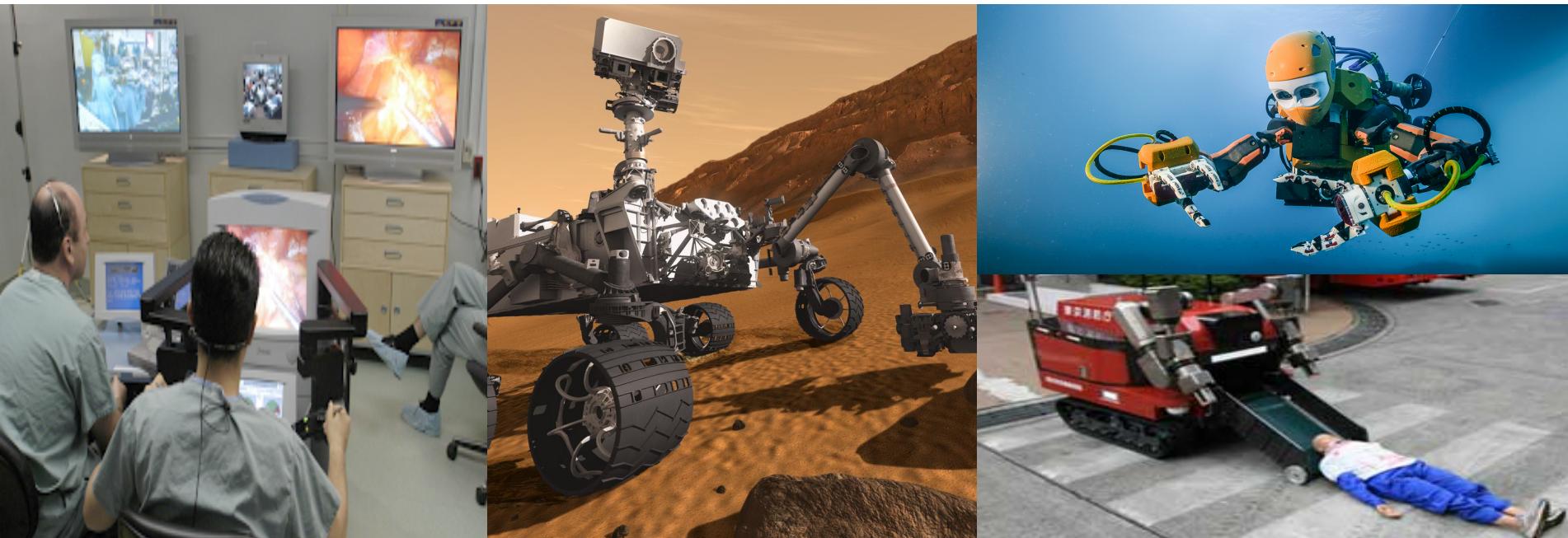


# Mitigating Network Latency in Cloud-Based Teleoperation using Motion Segmentation and Synthesis

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Ken Goldberg and Somayeh Sojoudi

Department of EECS, UC Berkeley

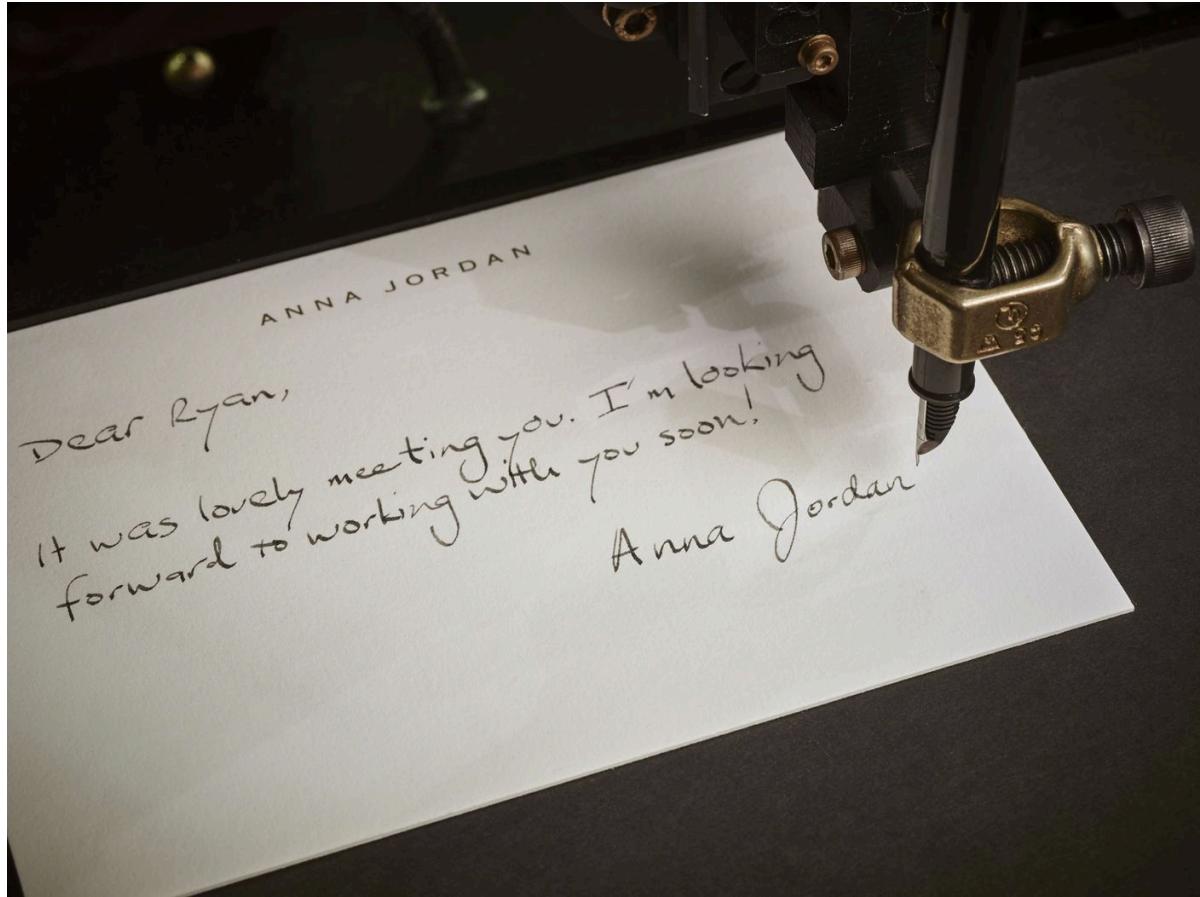
# Applications of Teleoperation



- Shamaei, Che, Goldberg, and Okamura. A paced shared-control teleoperated architecture for supervised automation of multilateral surgical tasks. 2015.
- Fong, and Charles, Vehicle teleoperation interfaces, 2001.
- Khatib, Yeh, Brantner, Soe, Kim, Ganguly, and Mullins Ocean one: A robotic avatar for oceanic discovery. 2016

# Teleoperate a Dynamic Robot to Draw Handwritten Letters

- Postcards
- Wedding invitations
- Teleoperate your friend's robot to create a "handwritten" postcard.
- **We may be able to do this over the internet using Cloud Robotics**



# Cloud Robotics and Fog Robotics

## Cloud Robotics



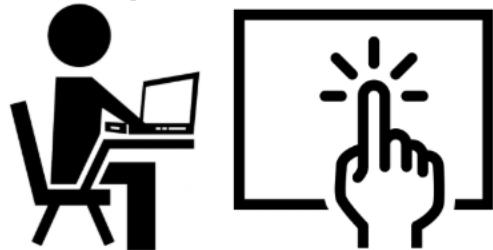
## Fog Robotics



- Kehoe, Patel, Abbeel, Goldberg, *A Survey of Research on Cloud Robotics and Automation*, 2015
- Tanwani, Mor, Kubiatowicz, Gonzalez, Goldberg, *A Fog Robotics Approach to Deep Robot Learning*, 2019
- Tian, Tanwani, Chen, Ma, Zhang, Huang, Goldberg, Sojoudi, *A Fog Robotic system for Dynamic Visual Servoing*, 2019

# Direct Teleoperation

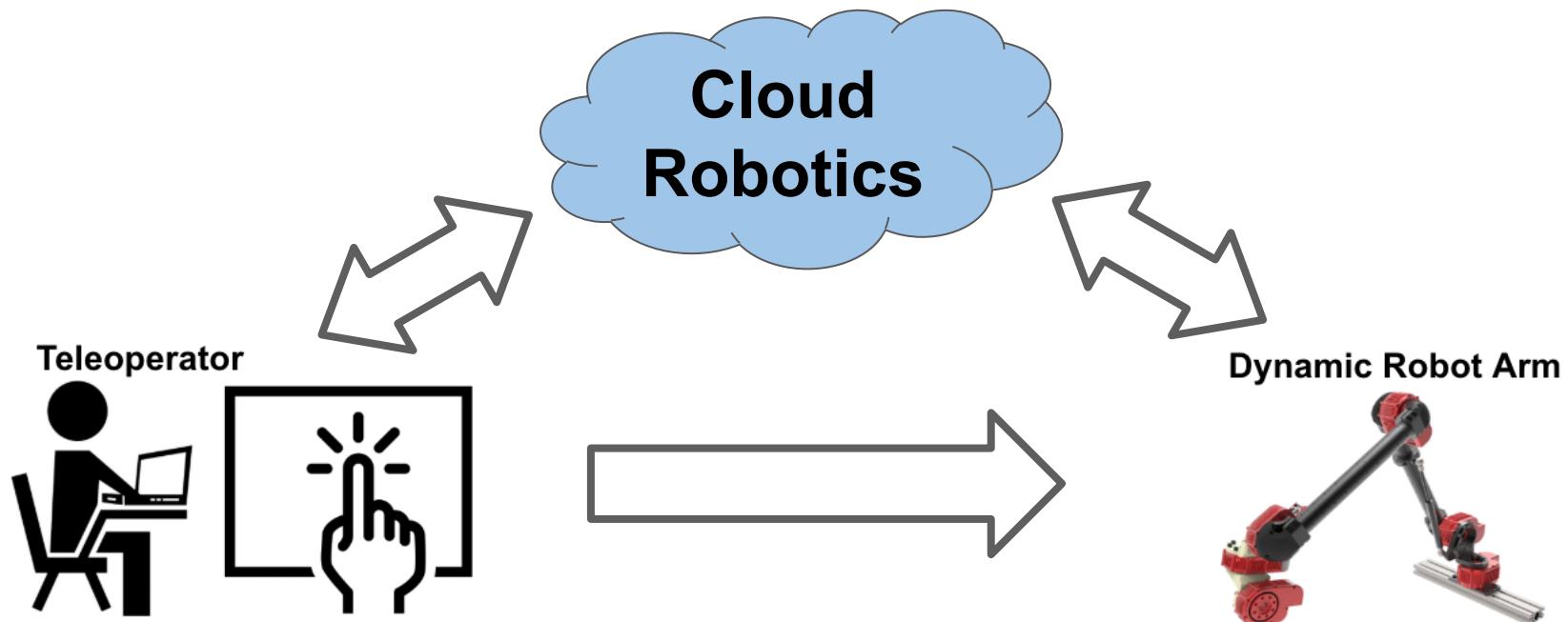
Teleoperator



Dynamic Robot Arm

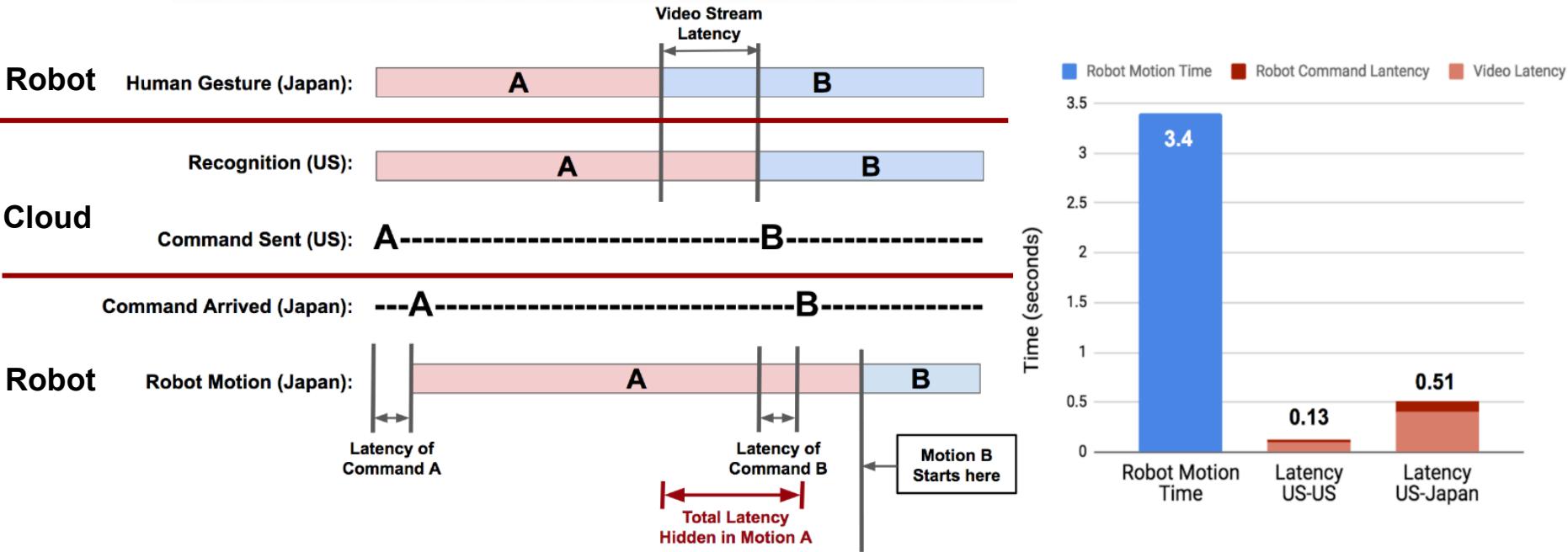


# Cloud Based Intelligent Teleoperation



**Unpredictable Network Delays**

# Idea: Hide Network Latency within Robot Motion Execution



## Shared Autonomy Motion Segmentation, Recognition, and Synthesis

# Related Work

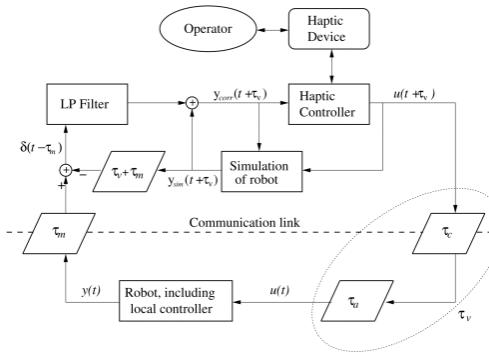
## Drawing Handwritten Letters



Borio, Calinon, Fol  
Laymarie, IROS 2016

Borio, Fol Leymarie,  
Calinon, Springer, 2019

## Dealing with Network Latencies



Smith, Christensen, IROS 2009

Ajoudani, Tsagarakis, Bicchi,  
IJRR, 2012

Tanwani, Calinon, IROS 2017

Chinchali, Pavone, RSS, 2019

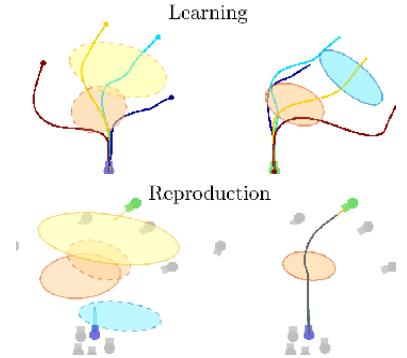
## Teleoperate Dynamic Robots



Smith, Bratt, Christensen,  
Neural Networks, 2008

Tian, Goldberg, Sojoudi,  
ICAR, 2019

## Motion Segmentation, Recognition, and Synthesis



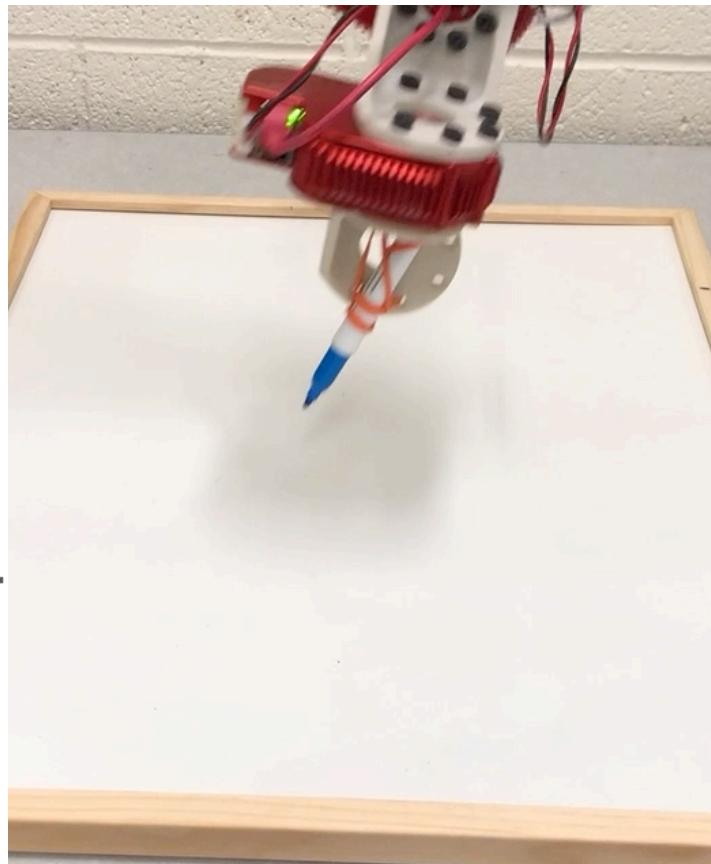
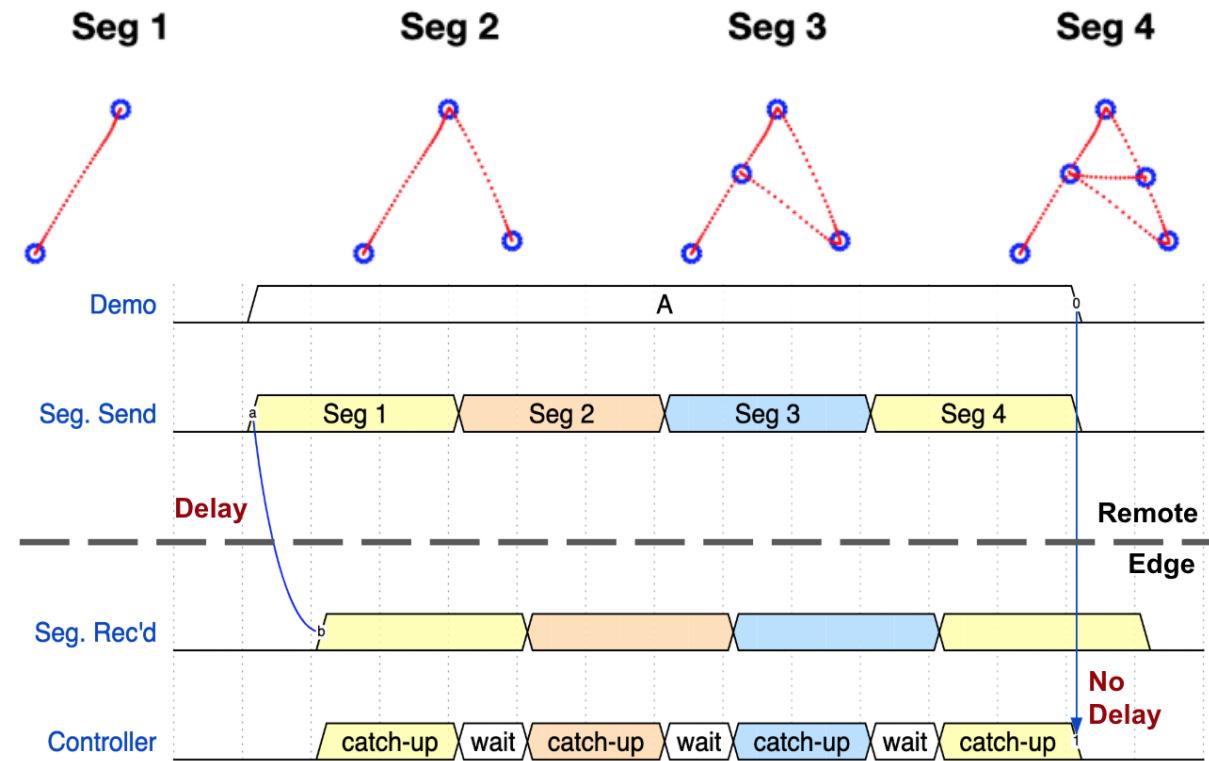
Aaro, Kragic, RAS, 2007

Calinon, Guenter, Billard, IEEE  
Transactions on Systems, Man,  
and Cybernetics 2007

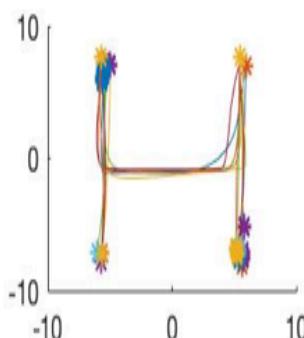
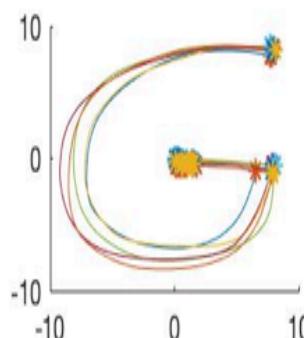
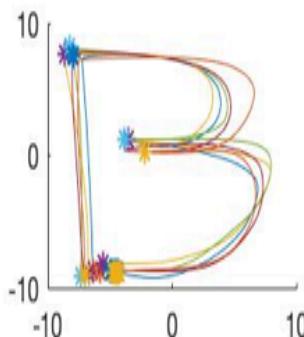
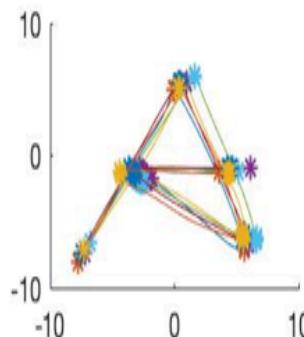
Meier, Theodorou, Schaal,  
AISTAT, 2012

Tanwani, PhD Thesis, 2018

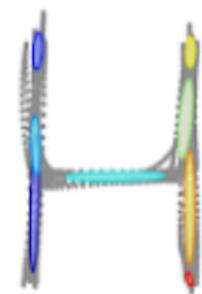
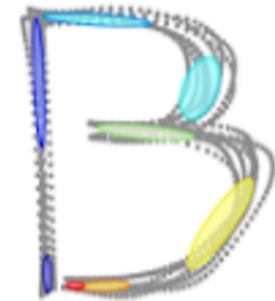
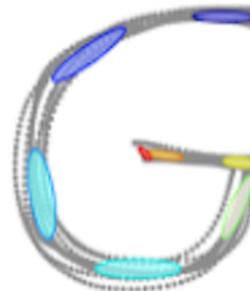
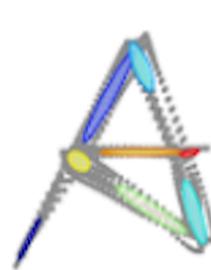
# Protocol I: Direct Teleoperation with Traj. Replay



# Motion Segmentation: Stationary Points vs. GMMs

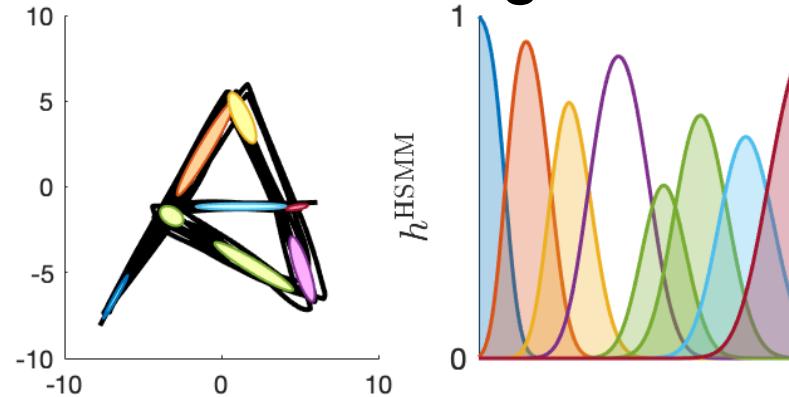


Stationary Points



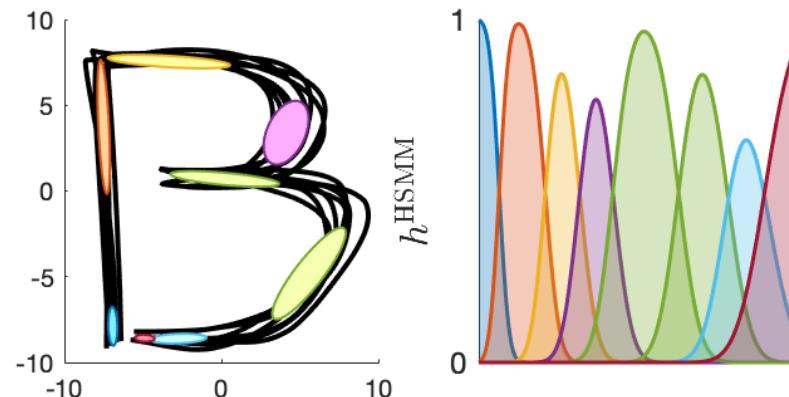
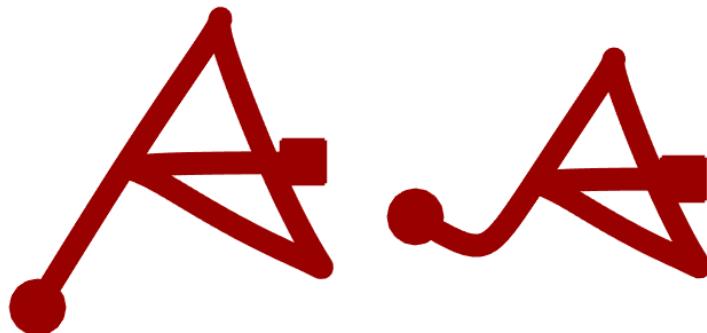
GMMs

# Motion Recognition



GMMs

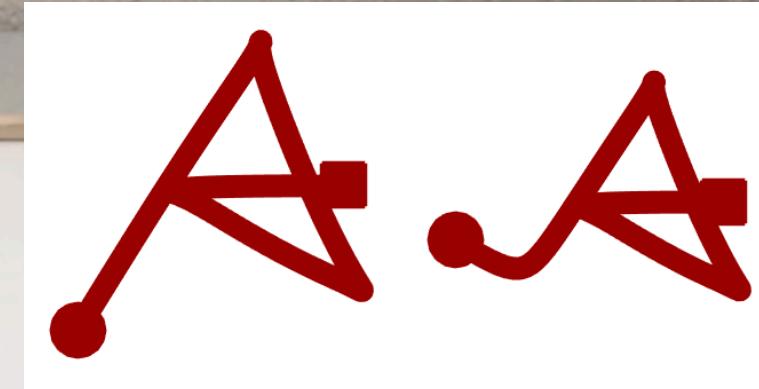
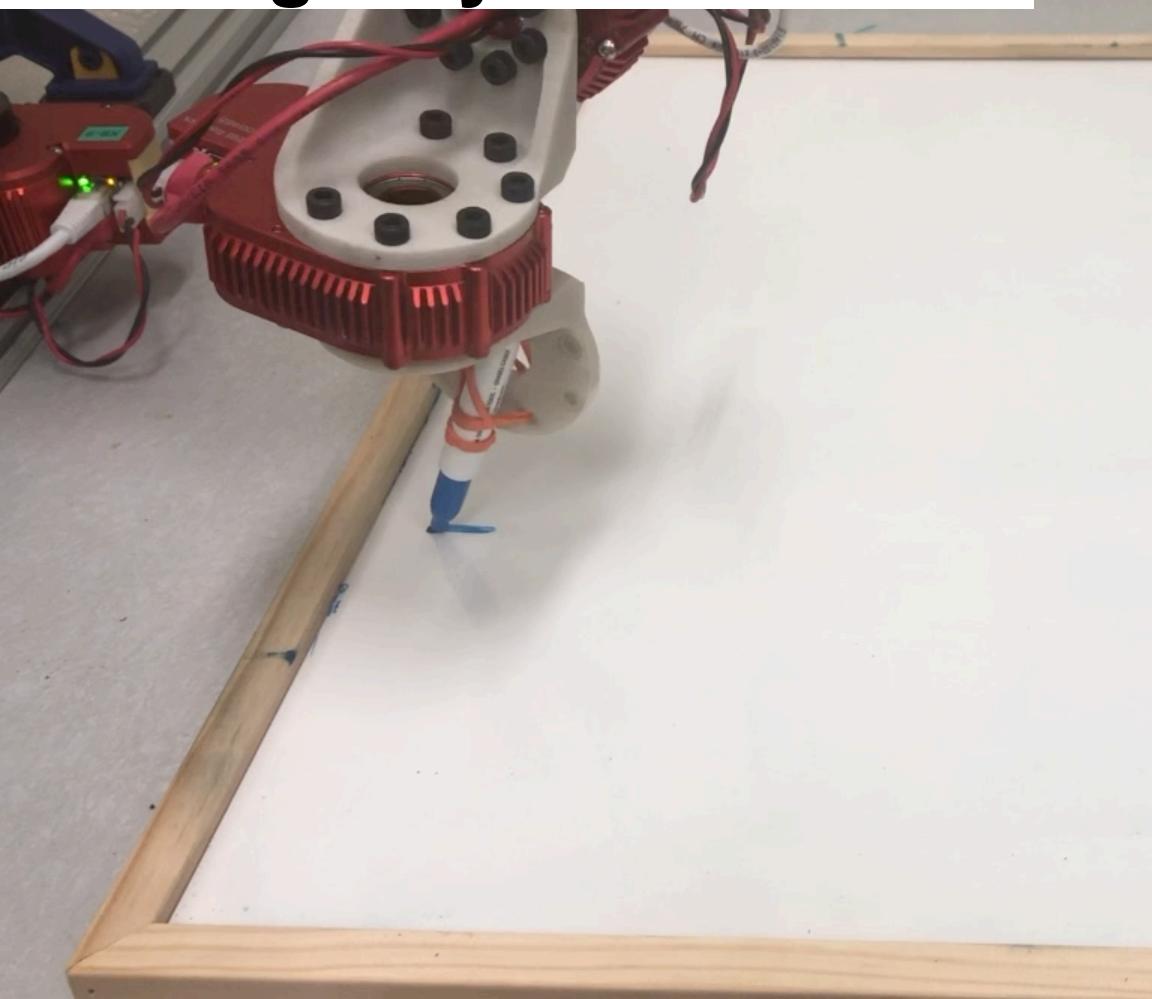
# Motion Synthesis



HSMMs

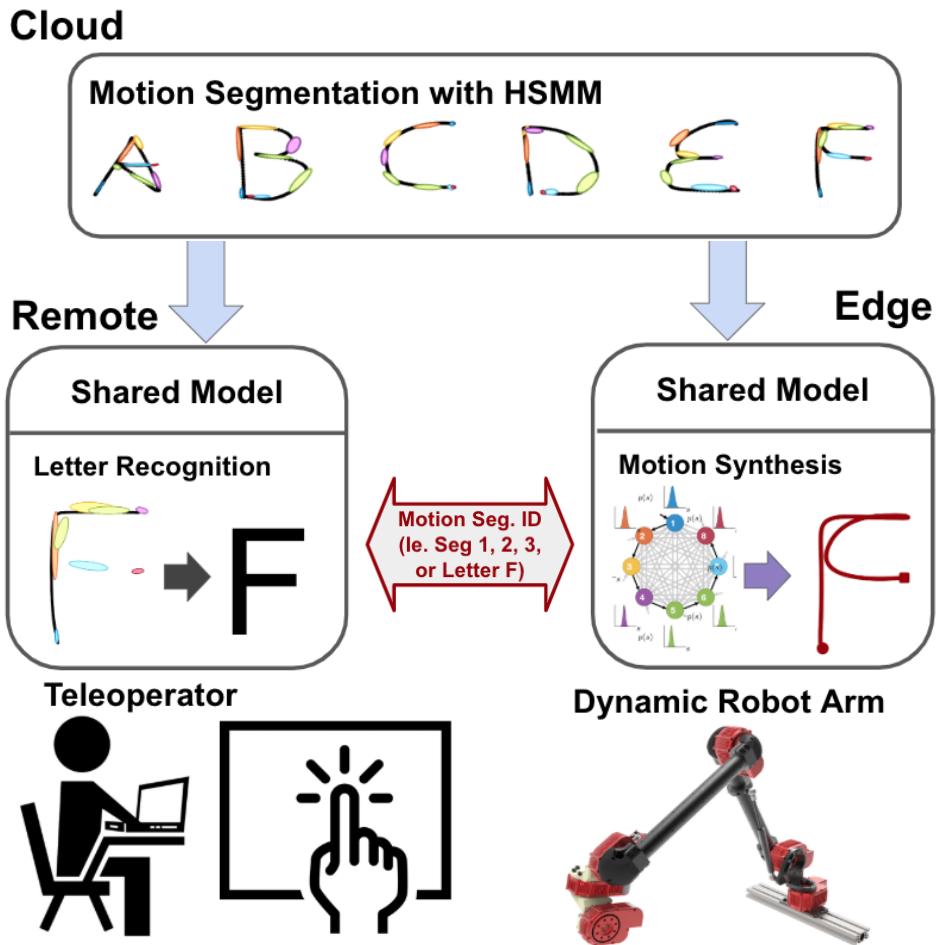
LQT: Linear Quadratic Tracker

# Drawing a Synthesized “A”

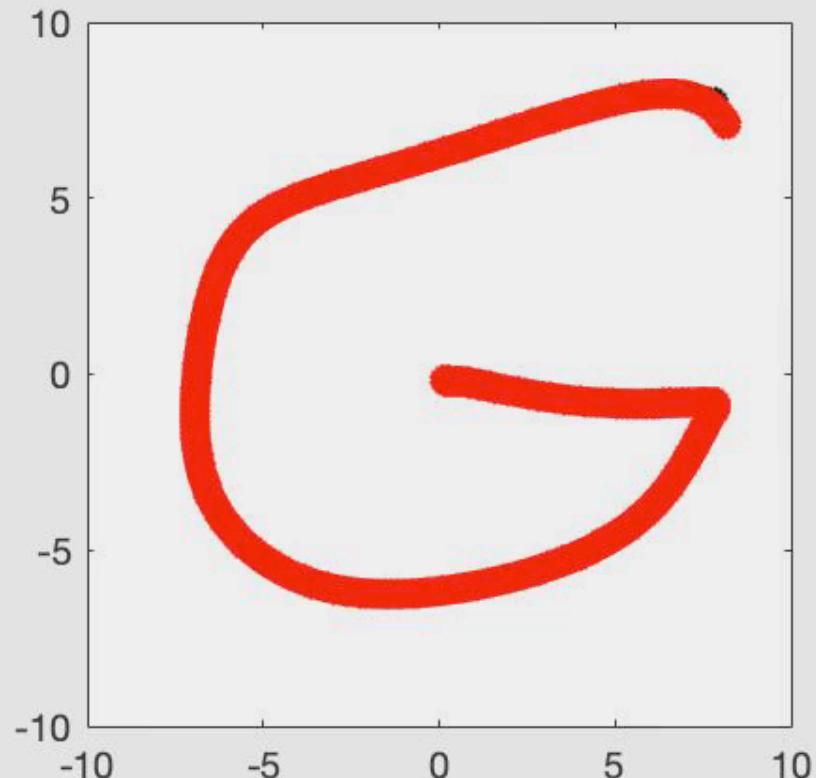
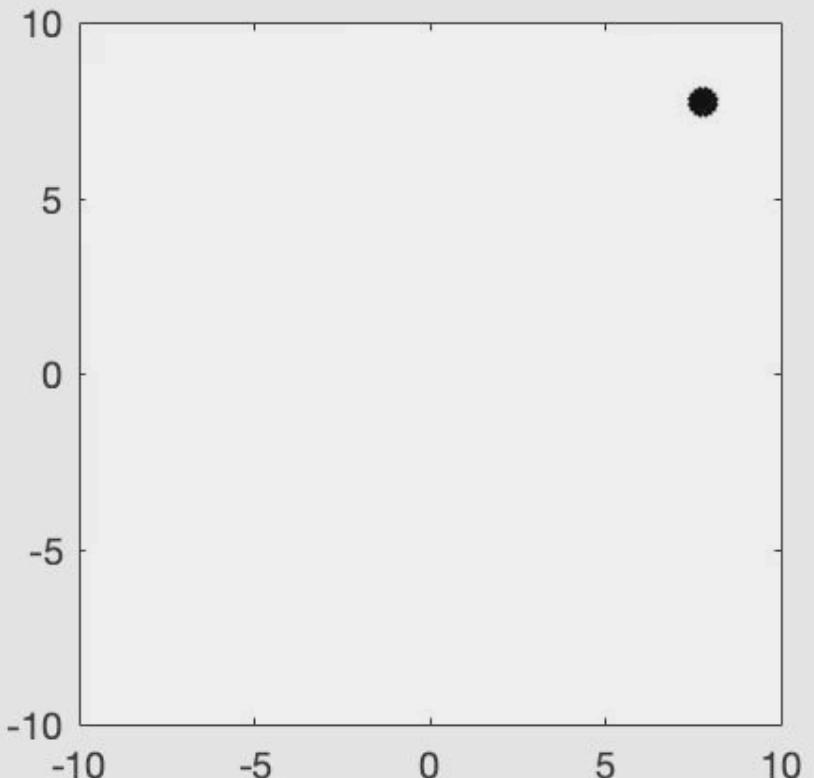


# System Architecture

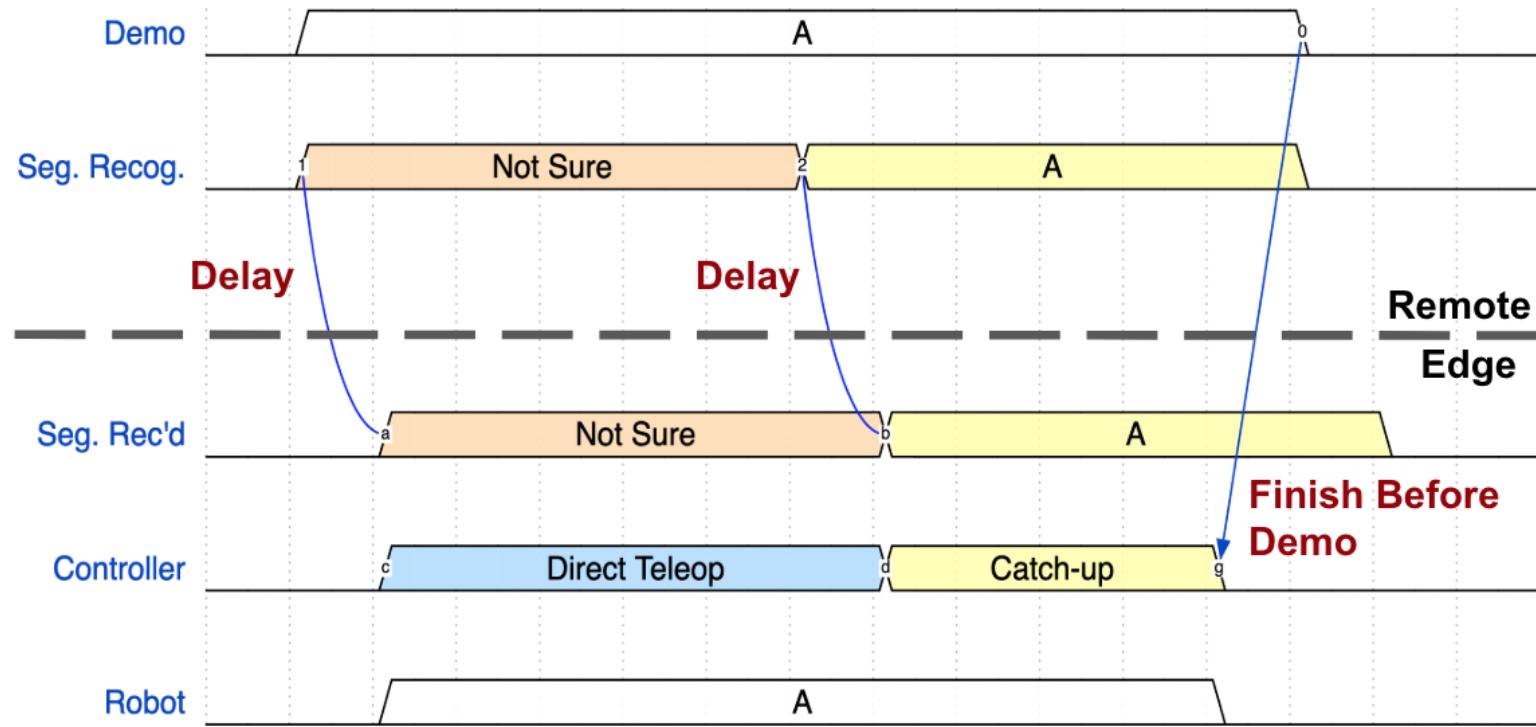
1. Motion Segmentation
2. Share Learned Models
3. Motion Recognition
4. Motion Synthesis



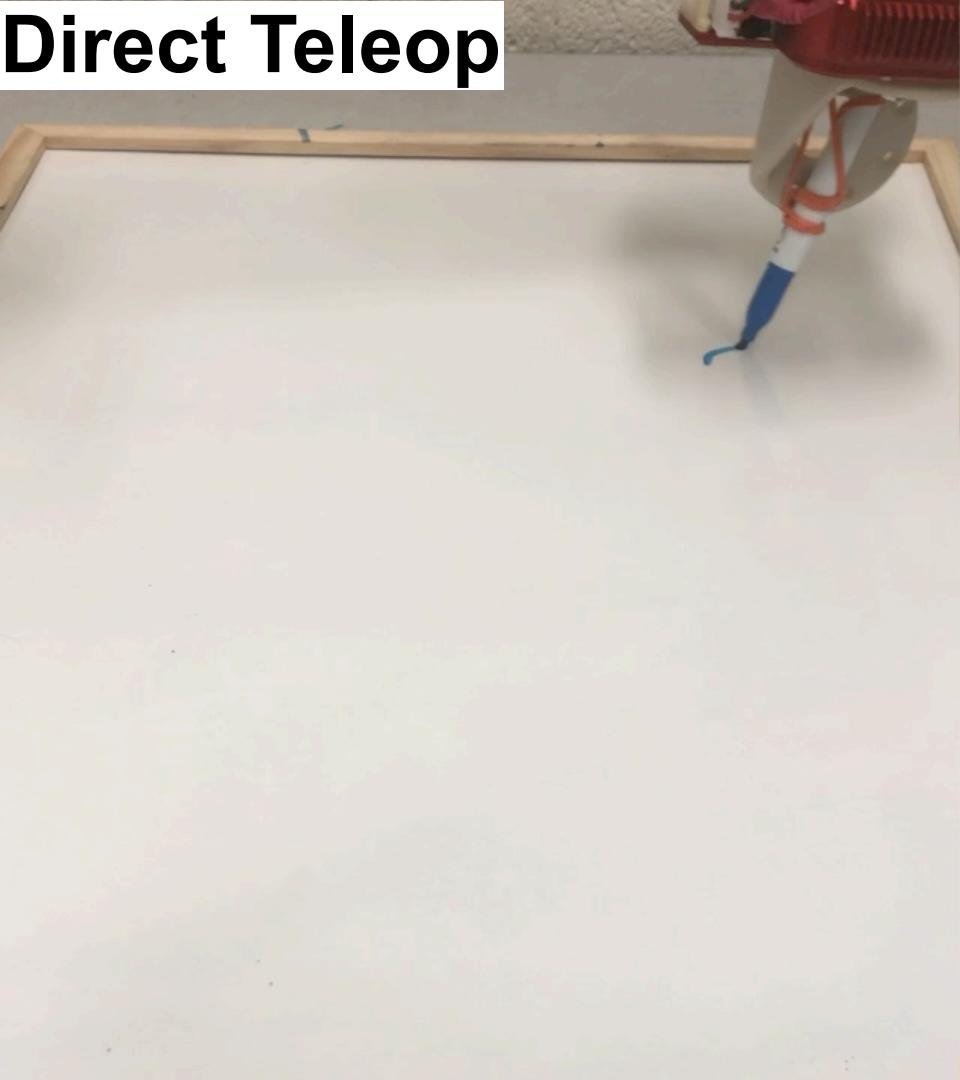
# Protocol Recognize and Finish in Simulation



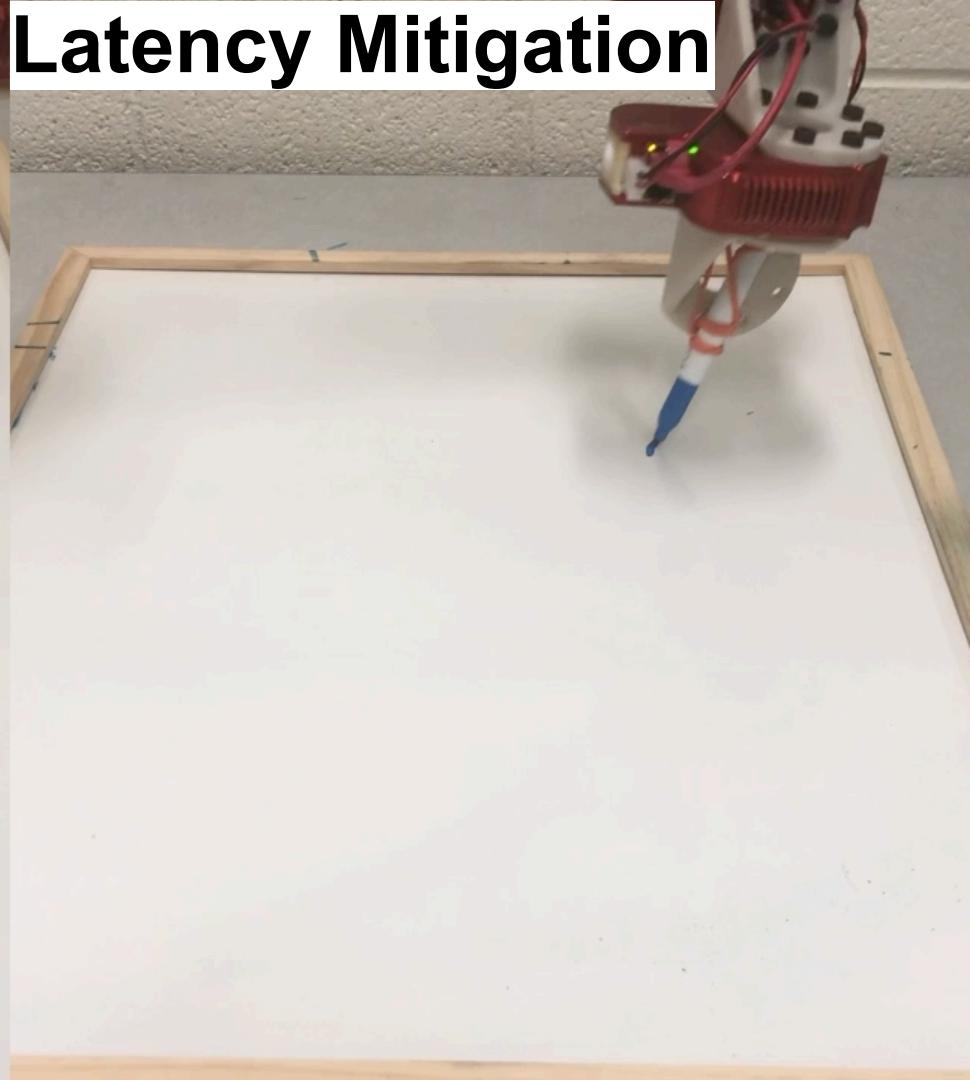
# Latency Mitigation Protocol: Recognize and Finish



# Direct Teleop



# Latency Mitigation



# Acknowledgement

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## UC Berkeley

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Prof. Mark Mueller  
Prof. Ron Fearing

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## Additional Resources on Cloud Robotics

Video Demos: <https://tinyurl.com/y2ex5844>

Cloud Robotics: <https://goldberg.berkeley.edu/cloud-robotics/>

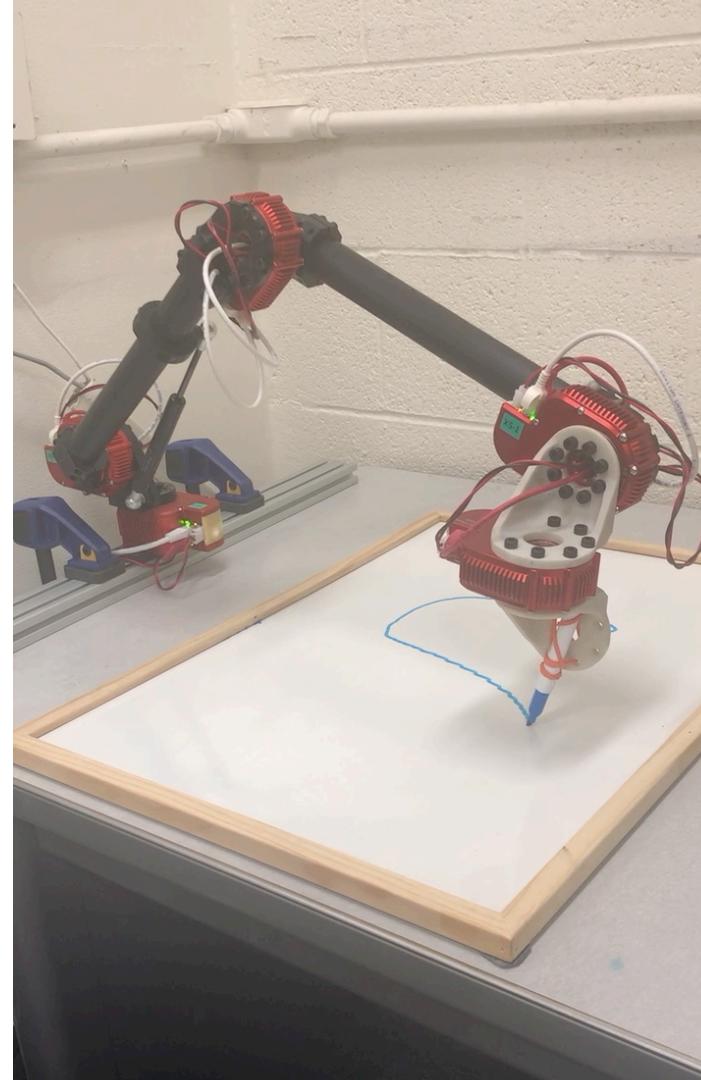
Fog Robotics: <https://sites.google.com/view/fogrobotics>

## AUTOLAB (Goldberg Lab)

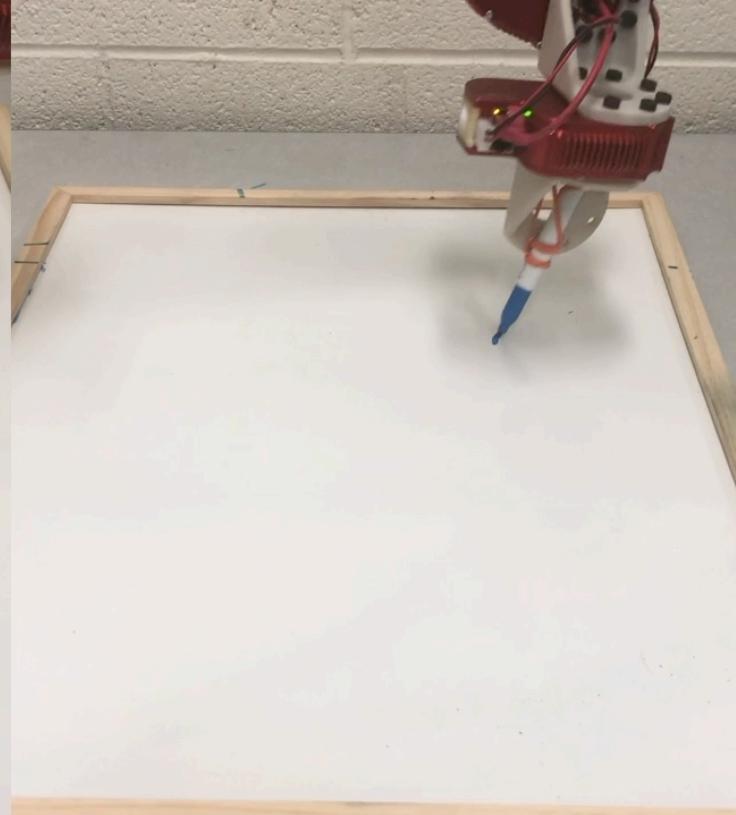
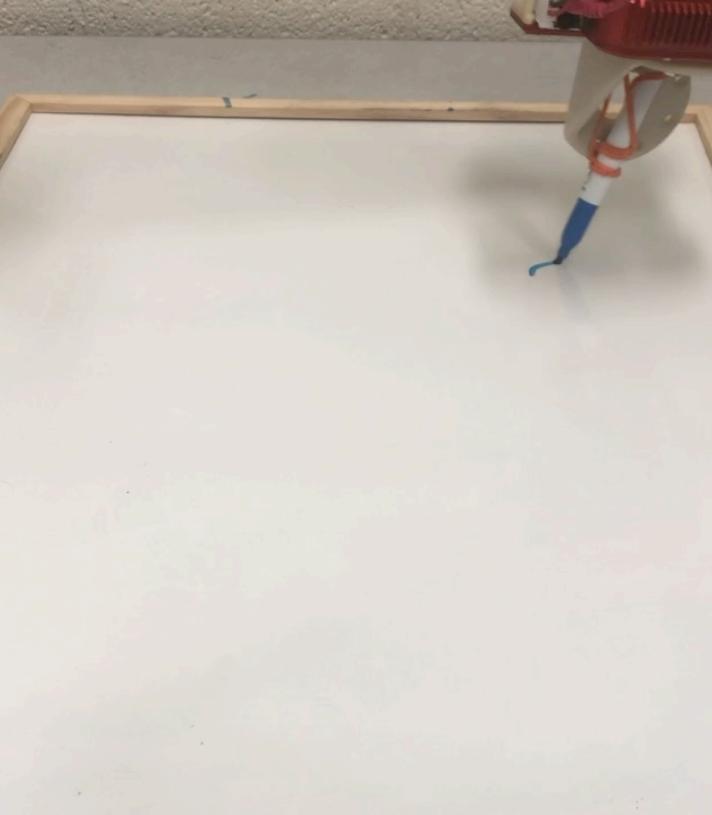
Prof. Ken Goldberg  
**Ajay Kumar Tanwani**  
Daniel Seita  
Michael Danielczuk

## Hebi Robotics

David Robinson  
Matthew Tesch  
Prof. Howie Choset



# Questions?



Email: Nan Tian neubotech@berkeley.edu  
Video Demos: <https://tinyurl.com/y2ex5844>  
Cloud Robotics: <https://goldberg.berkeley.edu/cloud-robotics/>  
Fog Robotics: <https://sites.google.com/view/fogrobotics>

# Limitations

- Introduce additional recognition delay
- Handwritten letter segments are short
- Hard to implement Protocols for multiple motion segment

