RESEARCH ON TAP

Robotics and Autonomous Systems

Wednesday, February 8, 2023

bu.edu/research/events

BOSTON UNIVERSITY

Boston University Office of Research

Agenda

- Welcome Remarks
- Presentations
  - Yannis Paschalidis
  - Christos G. Cassandras
  - Calin Belta
  - Roberto Tron
  - Wenchao Li
  - Alyssa Pierson
  - Douglas P. Holmes
  - Lou Awad
  - Terry Ellis
  - Eshed Ohn-Bar
  - Sheila Russo
  - Tommaso Ranzani
  - Andrew Sabelhaus
  - Sean Andersson
- Closing Remarks

Bio-Inspired Robust Autonomy

Yannis Paschalidis

Distinguished Professor of Engineering
(Electrical & Computer, Systems, and Biomedical)
Founding Professor of Computing & Data Sciences
Director, Hariri Institute

BU Rafik B. Hariri Institute for Computing and Computational Science & Engineering

BU Robotics & Autononous Systems Teaching and Innovation Center (RASTIC)

Training the next workforce in RAS in partnership with industry

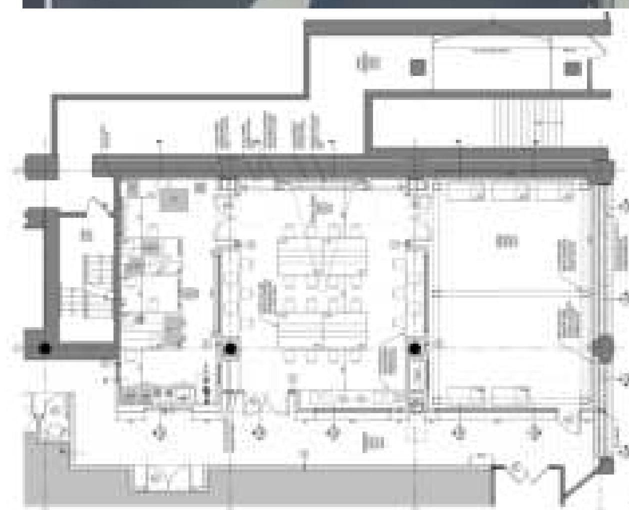
- Coming in the Fall of 2023 in the former CVS location on Comm. Ave.
- Supported by an $8.8M grant (50-50 with BU) from

MASSACHUSETTS TECHNOLOGY COLLABORATIVE

- with industry support

AVA ROBOTICS, AΣT Labs, Boston Scientific, intel, PRODRIVE TECHNOLOGIES, amazon robotics, GREENSIGHT, UBIROS ROBOTS. EVERYWHERE., massrobotics

- to enable student projects and research at the M.S. level, but also undergrads & Ph.D.'s



(Full) Autonomy is Hard

Quiz:

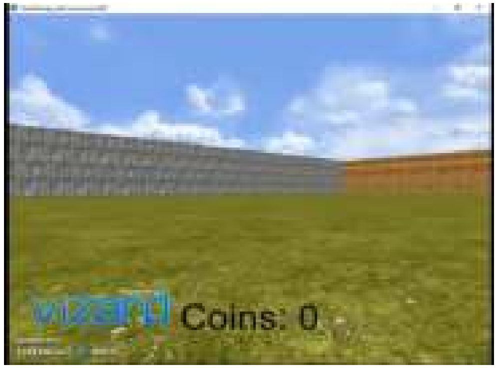
- "My guess as to when we would think it is safe for somebody to essentially fall asleep and wake up at their destination: probably toward the end of next year. I would say I am certain of that. That is not a question mark." **[2019]**
- "I thought the self-driving problem would be hard, but it was harder than I thought. It's not like I thought it'd be easy. I thought it would be very hard. But it was actually way harder than even that." **[2022]**
- **Who made both statements above?**

Mission-driven navigation in unstructured terrains is Harder

- Self-driving cars: Great sensors, well-mapped & structured terrain, few objects to recognize
- Animals and humans do it => Understand the science of animal/human navigation
- Bio-inspired & Neuro-inspired: Incorporate neuroscience-inspired understanding of how animals and humans navigate

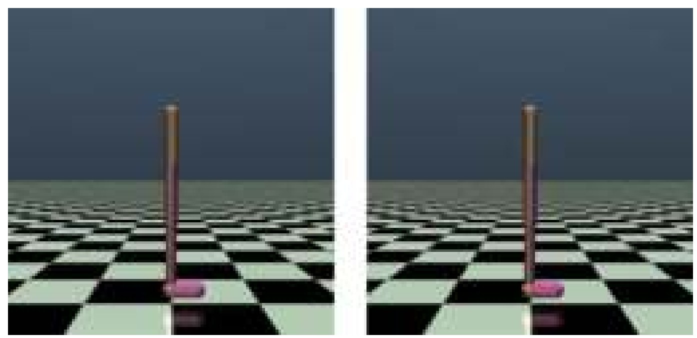
$7.5M ONR MURI

Bio-Inspired and Robust Autonomy



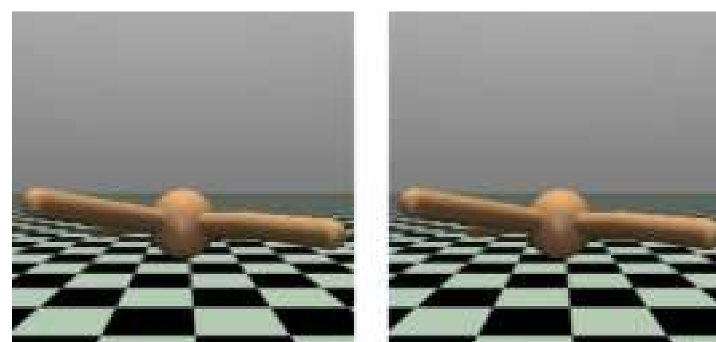
Methods to learn navigation policies from biological data:

- Learning a flat MDP policy (IEEE T. Autom. Control, 2019)
- Using moth data (PLOS Comp. Bio, 2020)
- Hierarchical Imitation Learning (AISTATS, 2021, IEEE CDC 2021)
- Achieving human-like performance using human data from a foraging game (with Stern & Hasselmo)



Robust and Sample-Efficient Reinforcement Learning:

- Robust policy optimization (AAAI 2021)
- Policy optimization with sample re-use (NeurIPS 2021)



Theory of Neural RL:

- Neural TD (ICLR 2023)

Network Optimization & Control Lab

Current students who contributed to this work: Jimmy Queeney, Zhiyu Zhang, Vittorio Giammarino, Nguyen Nguyen, Haoxing Tian, Arsenii Mustafin

Alumni: Dr. Henghui Zhu

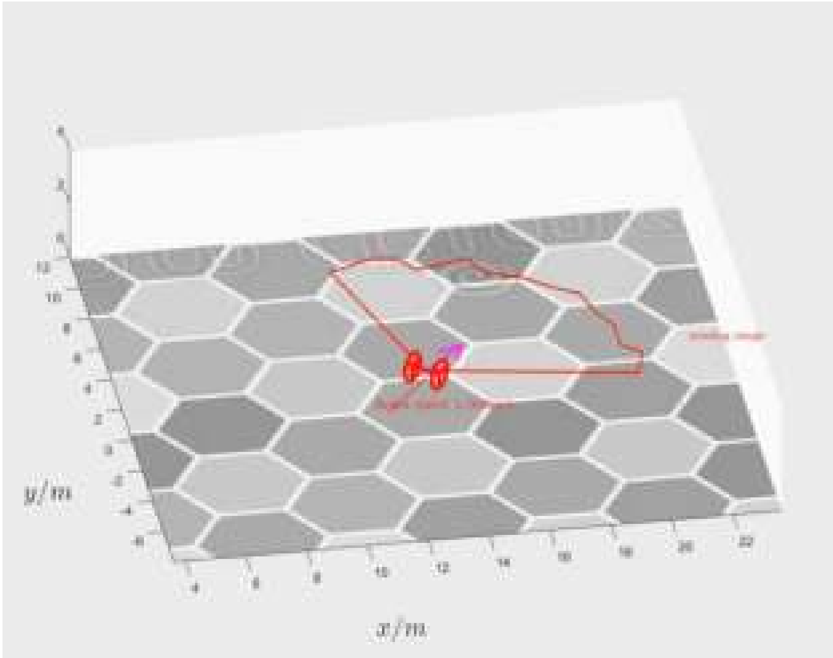
Collaborators: Alex Olshevsky, Christos Cassandras, Mike Hasselmo, Chantal Stern, Sean Andersson (RASTIC)

Safe Autonomous Systems In Robotics And The Internet Of Vehicles

Christos G. Cassandras

https://christosgcassandras.org/

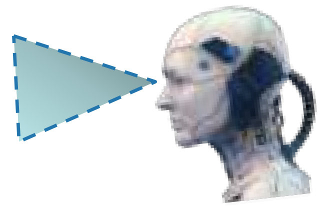
Distinguished Professor of Engineering
Head, Division of Systems Engineering
Professor of Electrical and Computer Engineering
Center for Information and Systems Engineering



Reach **destination**…

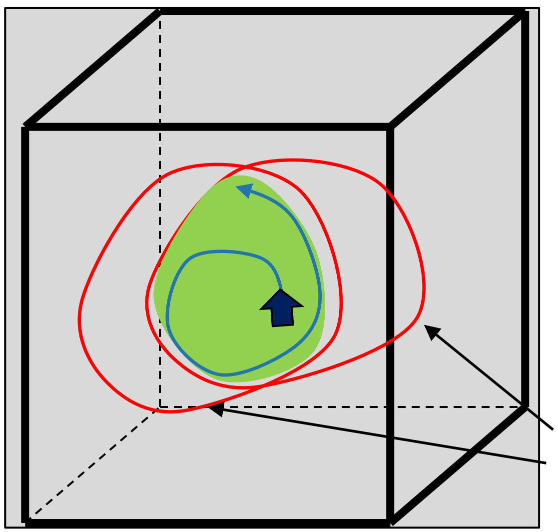
…**safely** (avoid obstacles with unknown locations)

…with **minimal effort** (minimize energy)



Humans reason reliably based on what they observe

Can we design AI-based autonomous systems which can guarantee SAFE (if not OPTIMAL) control actions?



***State space*: all states that autonomous system can access (positions, speeds,…)**

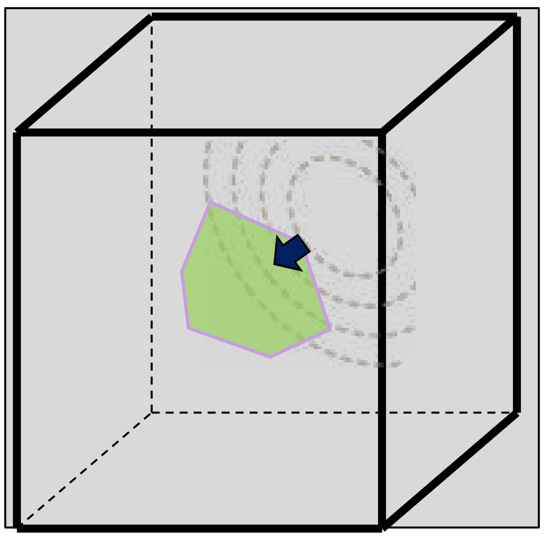
Safe sets

What is KNOWN or LEARNED about the autonomous system

SPEC'S

CONTROL

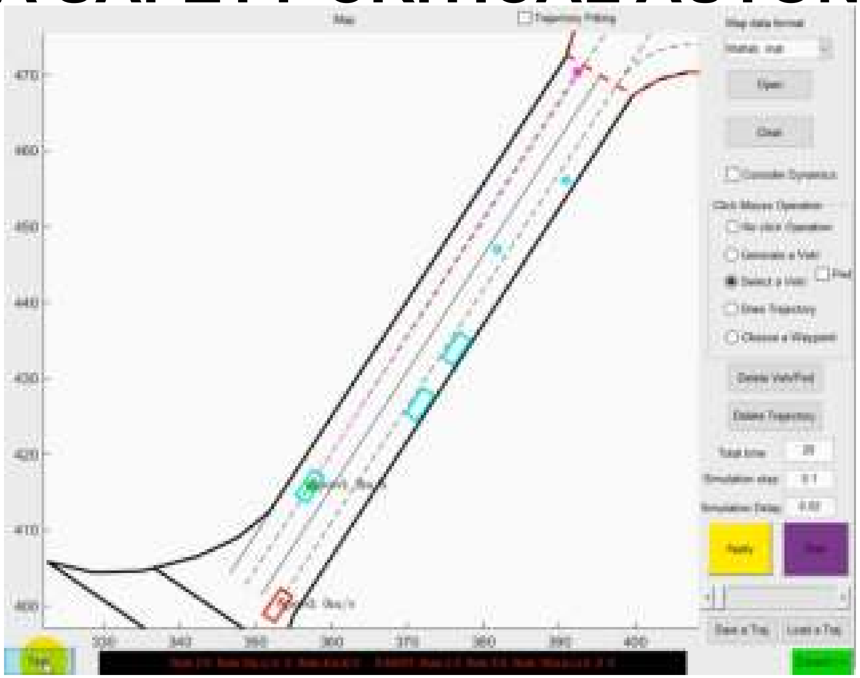
FORWARD INVARIANCE: Controller guarantees SAFETY over all future times



Feedback Control space

***Control Barrier Functions* (CBFs)**

A SAFETY-CRITICAL AUTONOMOUS SYSTEM

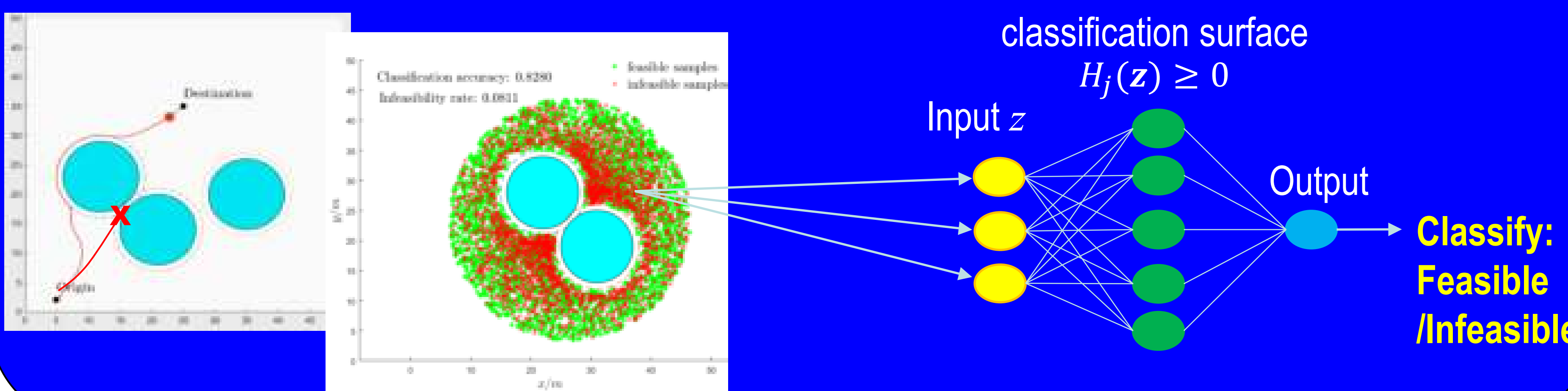


$$\underbrace{\begin{bmatrix} \dot{s} \\ \dot{n} \\ \dot{\mu} \\ \dot{v} \\ \dot{a} \\ \dot{\delta} \\ \dot{\omega} \end{bmatrix}}_{\dot{x}} = \underbrace{\begin{bmatrix} \frac{v\cos(\mu+\beta)}{1-n\kappa} \\ v\sin(\mu+\beta) \\ \frac{v}{l_r}\sin\beta - \kappa\frac{v\cos(\mu+\beta)}{1-n\kappa} \\ a \\ 0 \\ \omega \\ 0 \end{bmatrix}}_{f(x)} + \underbrace{\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}}_{g(x)} \underbrace{\begin{bmatrix} u_{jerk} \\ u_{steer} \end{bmatrix}}_{u}$$

- Trajectory tracking (mid-lane)
- State constraints (steering angle, speed)
- Control bounds (jerk, steering accel.)
- Obey prioritized list of traffic rules

REAL-TIME LEARNING IN ROBOTICS

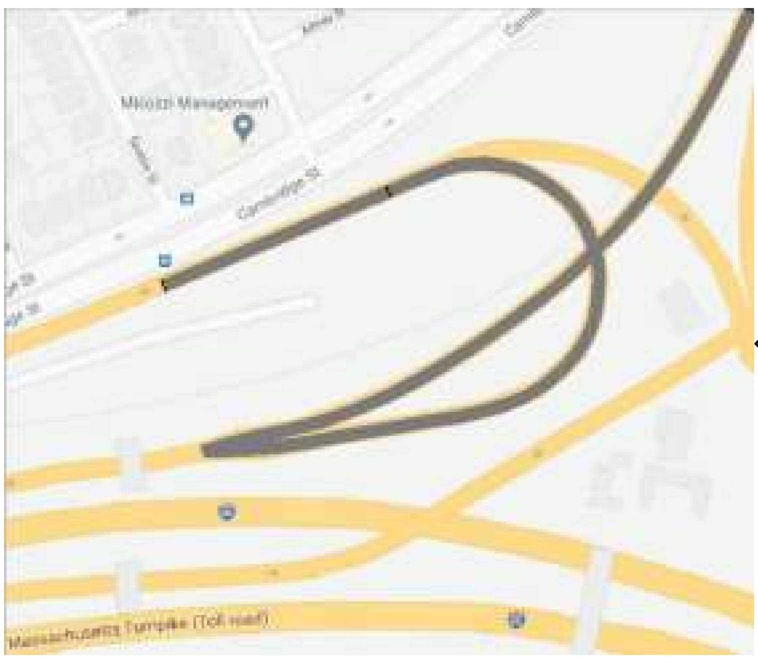
- **Learn safe trajectories on line before being forced to stop or enter unsafe sets**



WHY CAN'T WE IMPROVE TRAFFIC?

- Not enough controls → No chance to unleash the power of feedback!
- Not knowing other drivers' behavior → Drivers seek individual (selfish) optimum, not system-wide (social) optimum → *Price of Anarchy* (PoA)

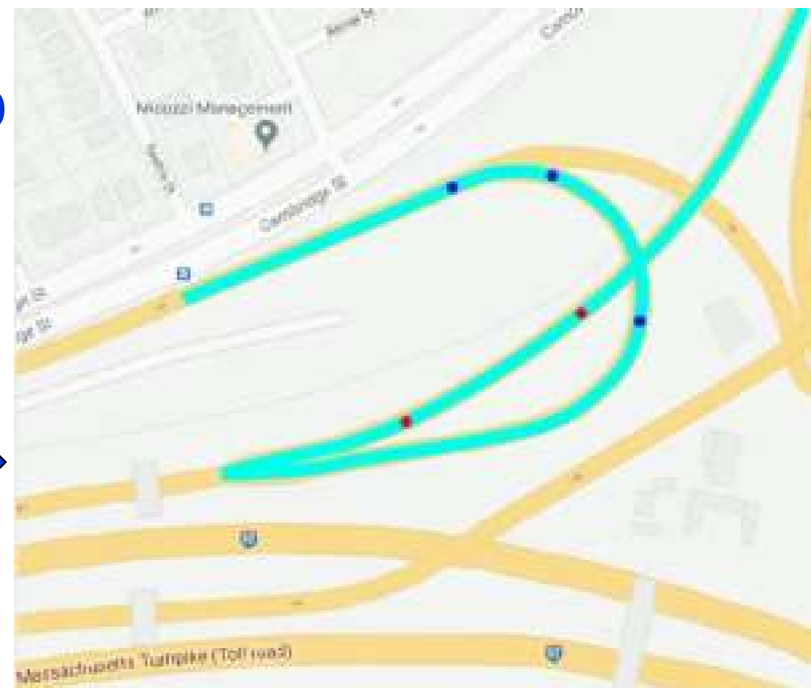
THE "INTERNET OF CA



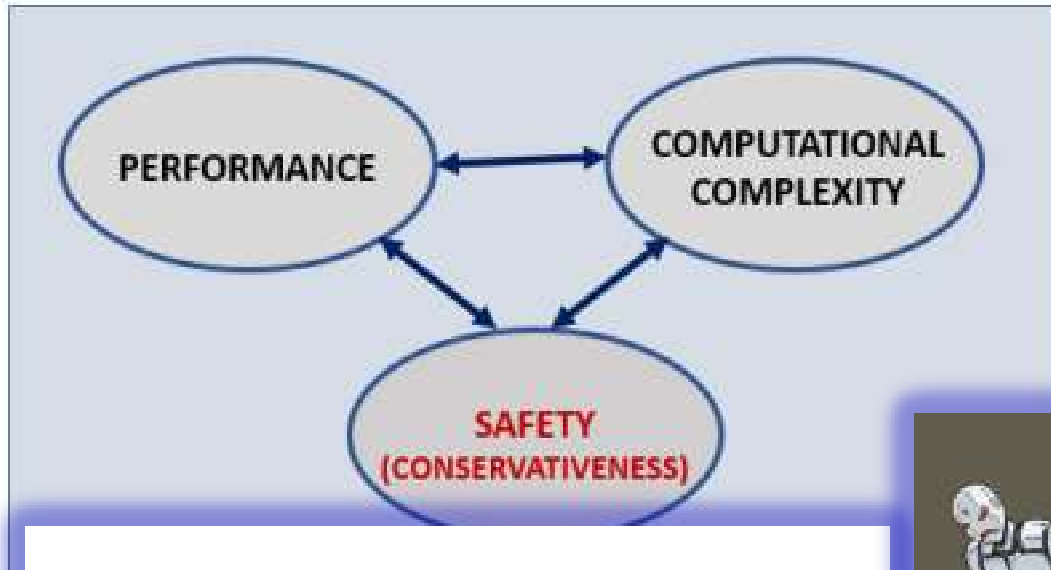
MERGING INTO MASS PIKE

Now...

Autonomous Vehicles



OPEN RESEARCH PROBLEMS



Design autonomous systems trading off:
Conservativeness for safety
v. Efficient performance
v. Computational Complexity

EARNING fit in?
between knowledge of system structure
at we have no good models for
(usually human behavior…)

Formal Methods for Autonomy

Calin Belta

Professor
Mechanical Engineering
Electrical and Computer Engineering
Systems Engineering
College of Engineering

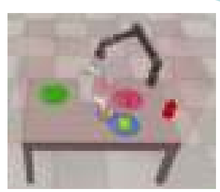
Formal Methods for Autonomy

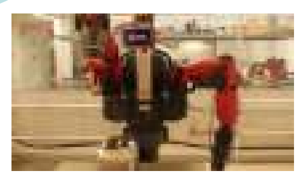
Formal Methods
- Expressive specification languages
- Formal proofs, safety guarantees
- Compositionality

Control Theory
- dynamics
- stability
- optimality

Machine Learning
- Unknown / uncertain systems
- Data-driven reasoning

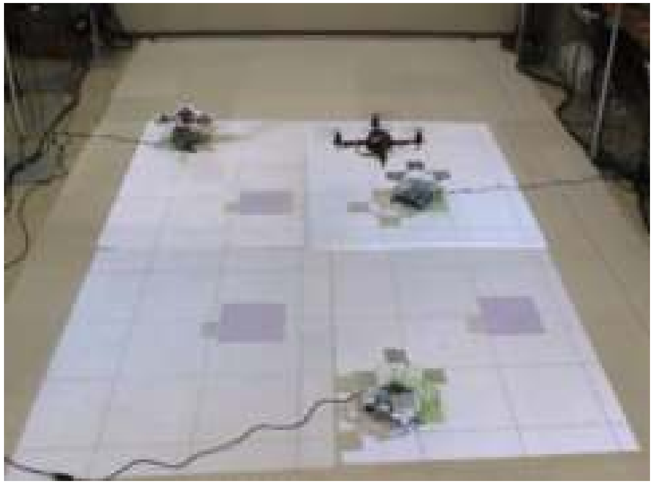
Autonomous Systems



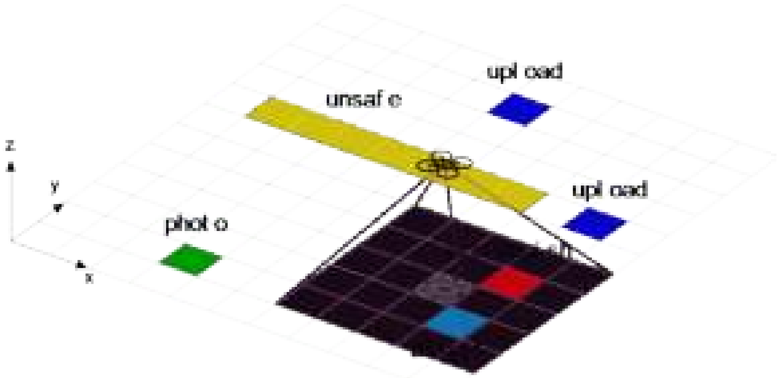


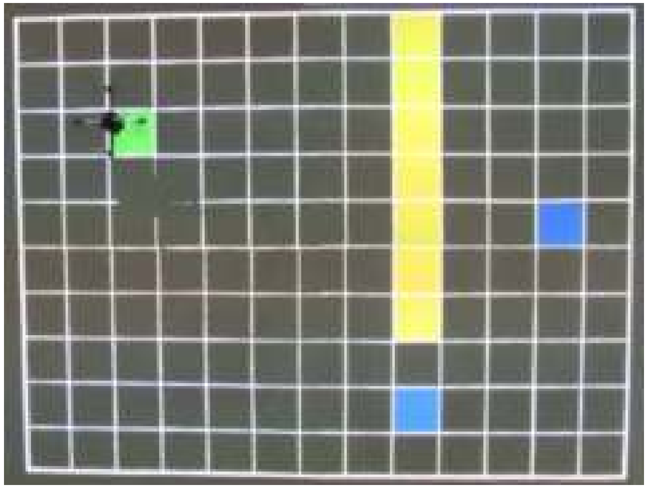
Persistent Surveillance

"Service site A for 2 time units within [0, 30] and site C for 3 time units within [0, 19]. In addition, within [0, 56], site B needs to be serviced for 2 time units followed by either A or C for 2 time units within [0, 10]."



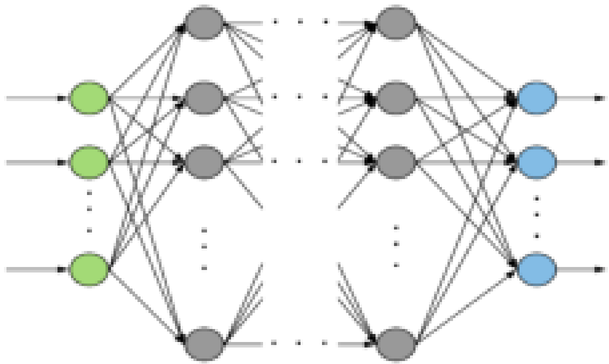
Spec: **Off-line:** "Keep taking photos and upload current photo before taking another photo. **On-line:** Unsafe regions should always be avoided. If fires are detected, then they should be extinguished. If survivors are detected, then they should be provided medical assistance. If both fires and survivors are detected locally, priority should be given to the survivors. Minimize travel time between consecutive uploads."

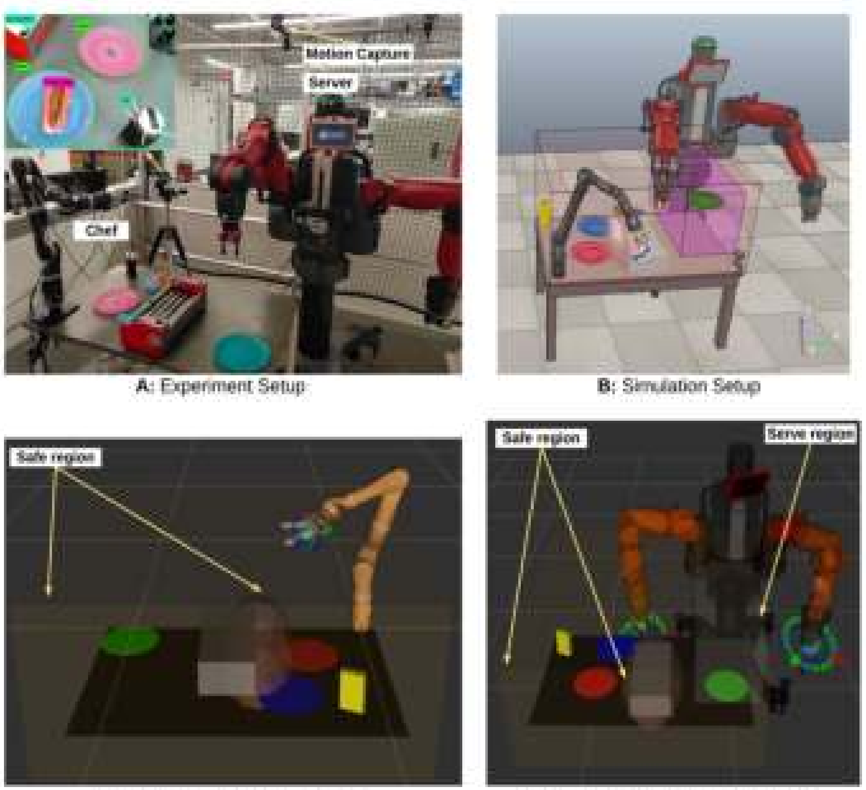




Ulusoy, Belta, RSS 2013, IJRR 2014

Making and Serving Hotdog





A: Experiment Setup

B: Simulation Setup

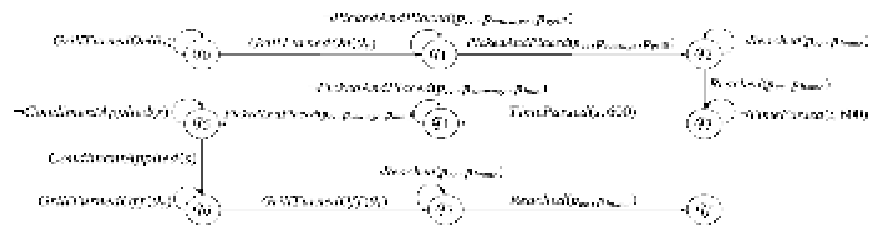
C: Jaco environment visualization

D: Baxter environment visualization

Serlin et.al., Science Robotics, 2019

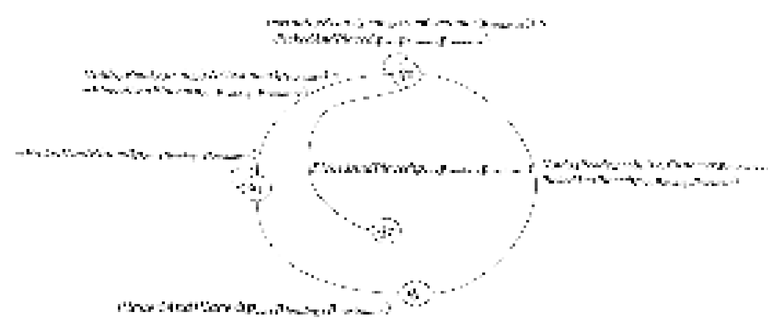
Chef (Jaco): Make a hotdog

Turn on grill and then place sausage on grill and then return to home position and then wait for 600 seconds and then place sausage on the bun and then apply ketchup and then turn off grill and then return to home position



Server (Baxter): Serve the hotdog when one is ready and there is a customer

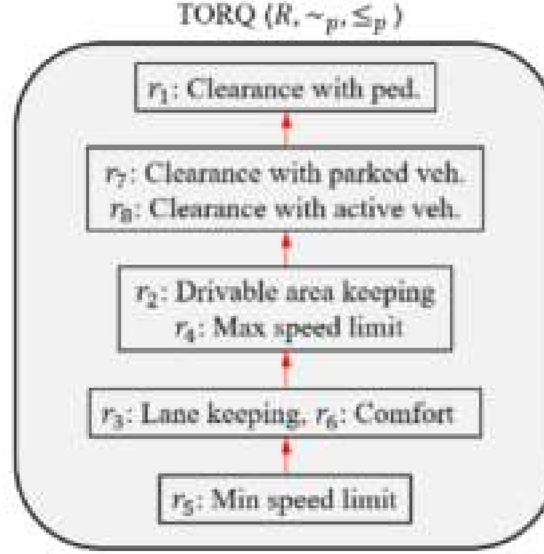
Eventually serve the hotdog and do not serve until hotdog is ready and customer detected



Motional

Autonomous Driving using Prioritized Rules

$$\min_u \int_0^T (u^T P u)dt$$



Subject to:

- Dynamics

$$\underbrace{\begin{bmatrix}\dot s\\ \dot n\\ \dot\mu\\ \dot v\\ \dot a\\ \dot\delta\\ \dot\omega\end{bmatrix}}_{\dot x} = \underbrace{\begin{bmatrix}\frac{v\cos(\mu+\beta)}{1-n\kappa}\\ v\sin(\mu+\beta)\\ \frac{v}{l_r}\sin\beta - \kappa\frac{v\cos(\mu+\beta)}{1-n\kappa}\\ a\\ 0\\ \omega\\ 0\end{bmatrix}}_{f(x)} + \underbrace{\begin{bmatrix}0&0\\0&0\\0&0\\0&0\\1&0\\0&0\\0&1\end{bmatrix}}_{g(x)} \underbrace{\begin{bmatrix}u_{jerk}\\u_{steer}\end{bmatrix}}_{u}$$

- Trajectory tracking (middle of current lane)
- State limitations (steering angle, vehicle speed, etc.)
- Control bounds (jerk, steering acc.)
- Minimum violation of a prioritized set of rules

(*Xiao, et.al.*, ICCPS2021)

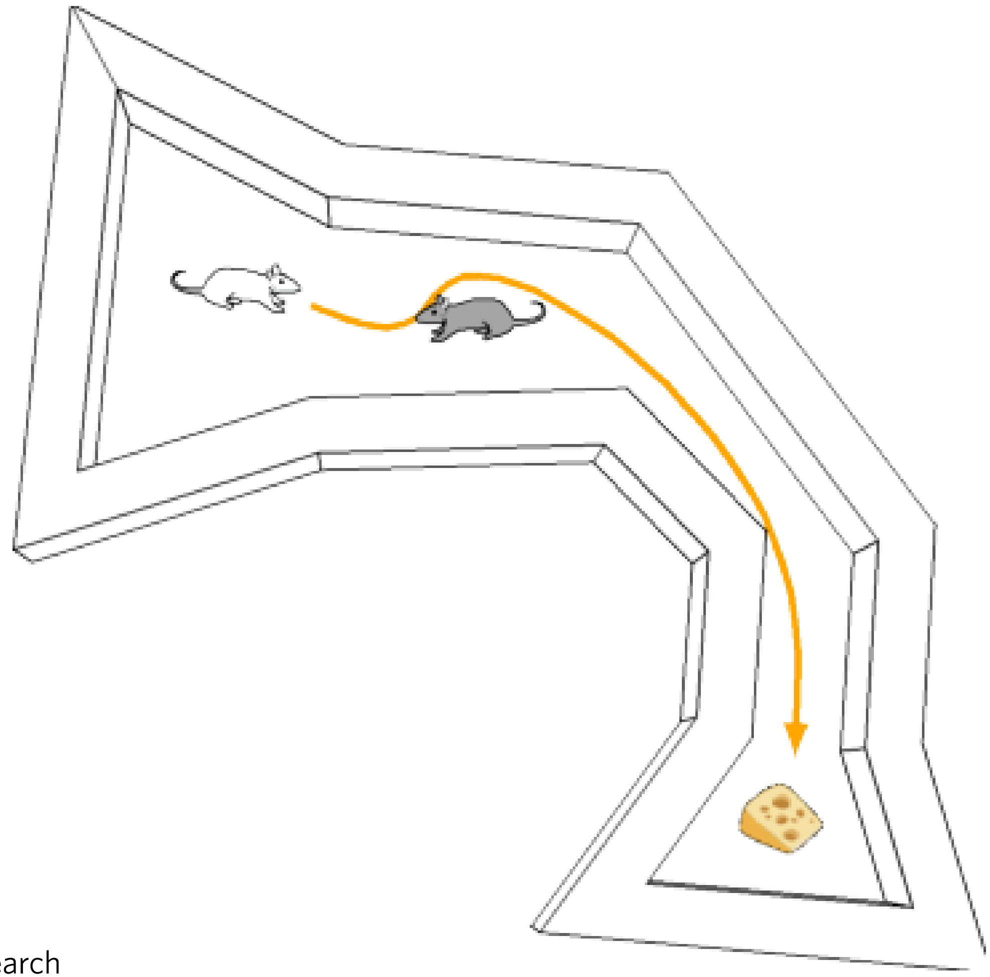
Navigation, Brains, Fields, and Linear Programming

Roberto Tron

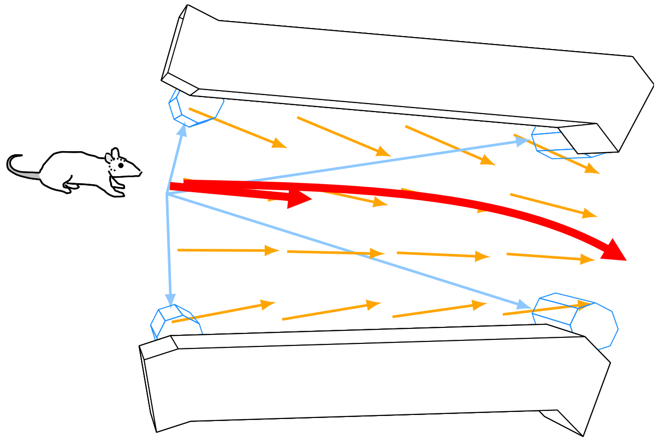
Assistant Professor
Mechanical and Systems Engineering
College of Engineering

Autonomous navigation

Reach the goal
"without thinking"
and "*robustly*"



Traditional path planning gives only a single open-loop path



Our approach

- Uses feedback from measurements
- Manipulates field on entire region

$$u = Ky$$

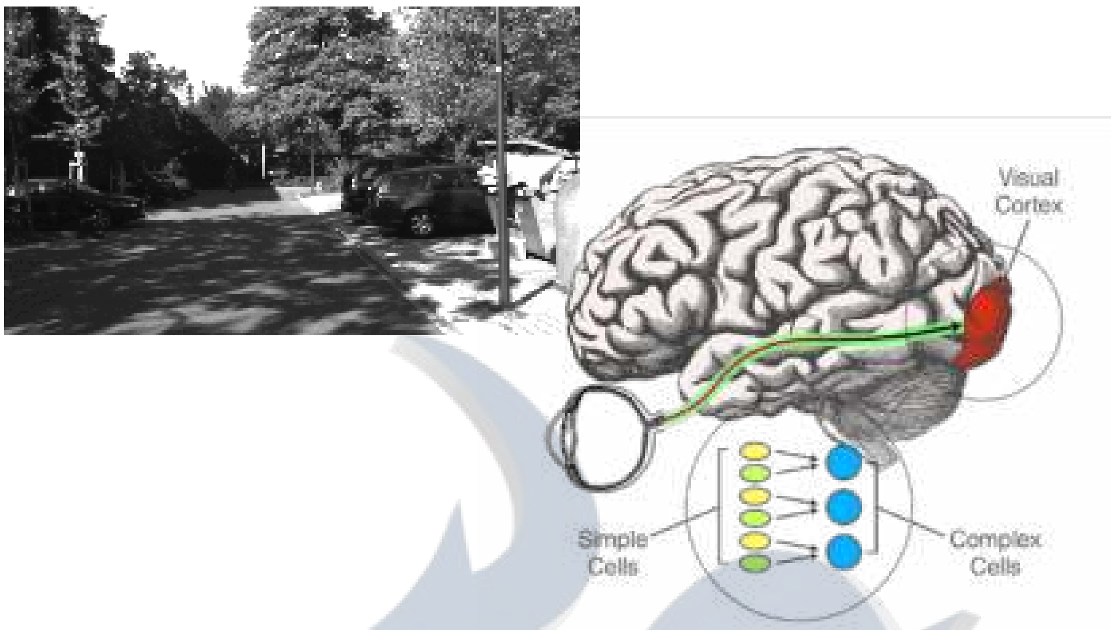
Linear Programming: Fast and optimal

Experimental results

Feedback control → works with deformations

Bio-inspired filtering

Formalize neuroscience models with convergence guarantees



Byzantine Resilience at Swarm Scale

Wenchao Li

Assistant Professor
Department of Electrical and Computer Engineering
College of Engineering

Robot Swarms

- Shape formation, search and rescue, surveillance & reconnaissance, cooperative target tracking & monitoring, collective transport, etc.

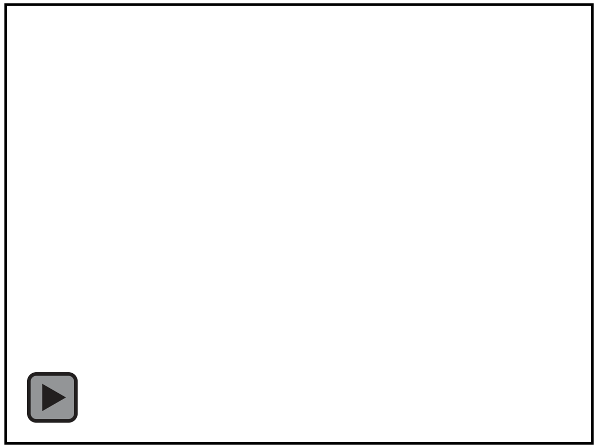
[www.theguardian.com/technology/2015/sep/18 /robot-swarms-drone-scientists-hive-mentality]

A swarm of robots performing target tracking

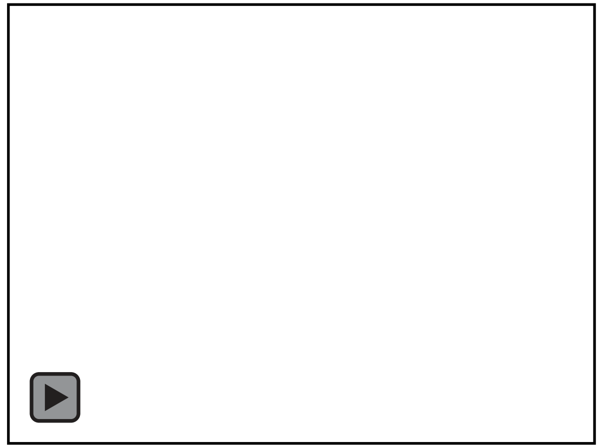
[Youtube: Drone Christmas Show Darling Harbour Sydney]

- Security and reliability challenges:
  - Faulty or malicious robots can easily disrupt the function and safety of the swarm
  - Byzantine threats in multi-robot systems: an unknown subset of the robots is allowed to have arbitrarily different behaviors relative to the cooperative robots

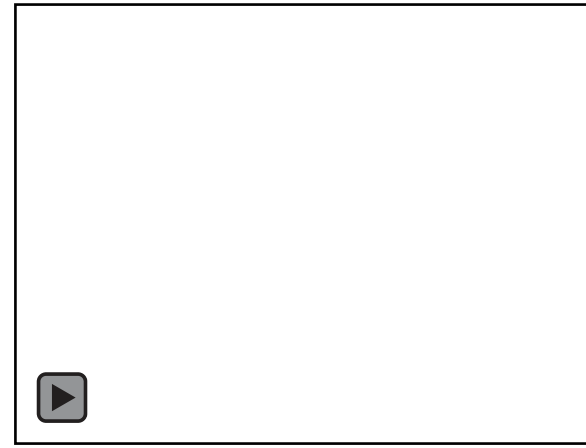
A swarm of robots performing target tracking: Any robot who does not directly observe the target computes a **consensus** of where the target is based on information communicated by neighboring robots.



No Byzantine Robots



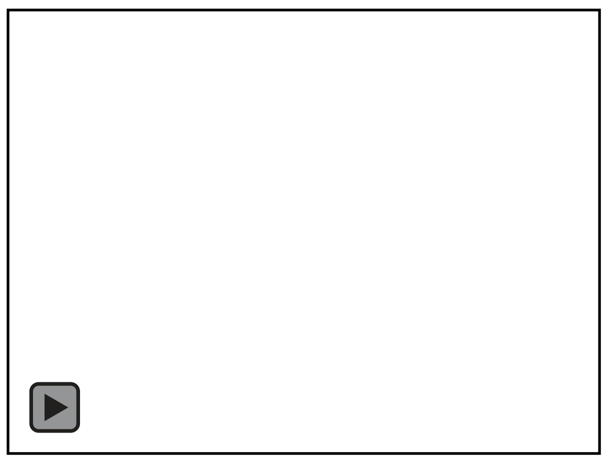
With Byzantine Robots (in red)



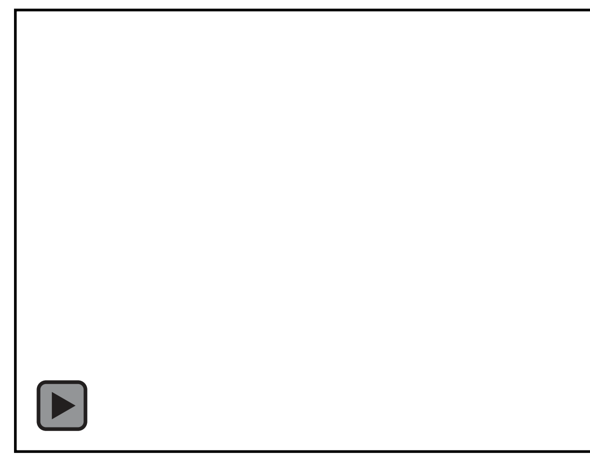
Mitigation using W-MSR[1]

Our breakthrough for Byzantine resilience:

- A decentralized blocklist protocol (DBP) based on inter-robot accusations.
- More scalable and less connectivity requirement compared with W-MSR.



Mitigation using DBP[2]



60 Byzantine 100 Cooperative

1. LeBlanc et al. Resilient Asymptotic Consensus in Robust Networks. IEEE Journal on Selected Areas in Communications, 2013.
2. Wardega et al. Byzantine Resilience at Swarm Scale: A Decentralized Blocklist Protocol from Inter-robot Accusations. AAMAS 2023.

Designing Semi-Cooperative Robot Teams

Alyssa Pierson

Assistant Professor
Mechanical Engineering
College of Engineering

Coordinating Multi-Agent Systems

How do we design teams with:

Performance variations?

Uncertainty?

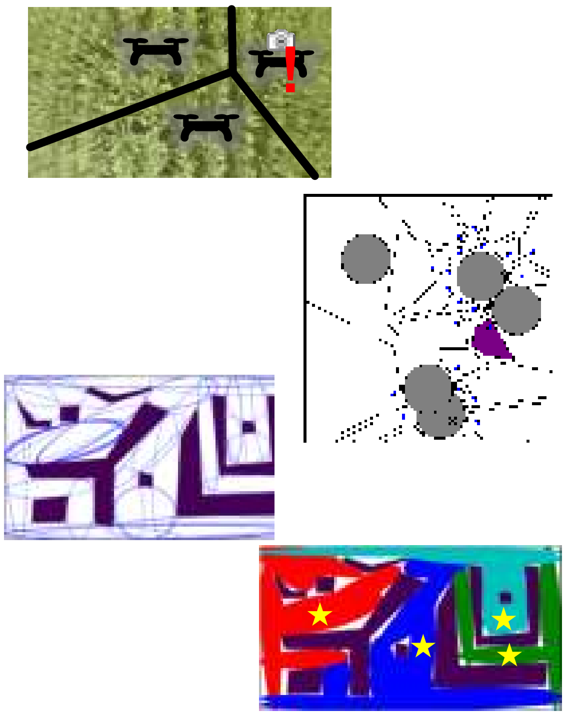
Non-cooperative teammates?

Human teammates?

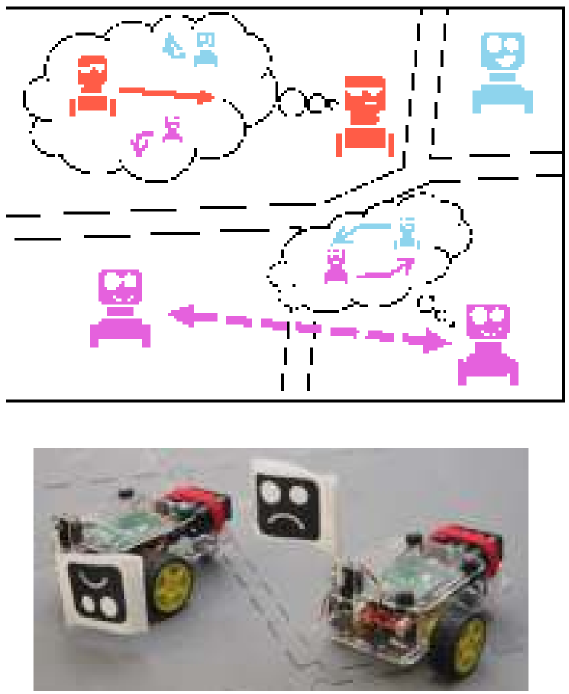
All cooperative
Equal performance

Malicious agents

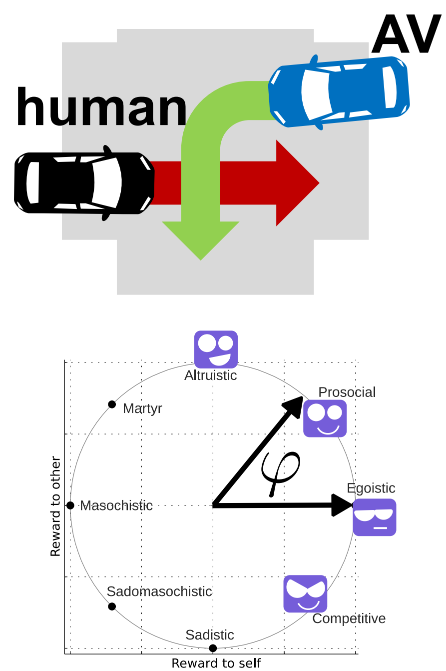
Engineering Group Autonomy



Geometric Methods

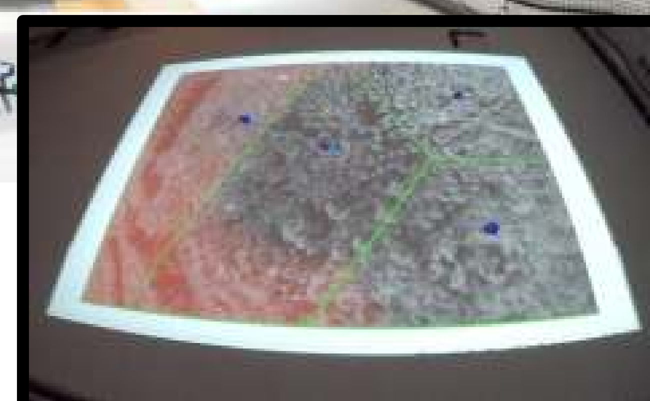


Controls & Game Theory



Dynamic Interactions

Engineering Group Autonomy



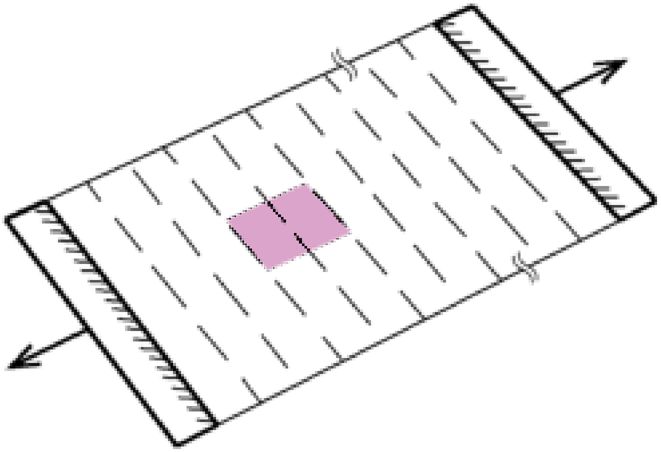
Functional Kirigami

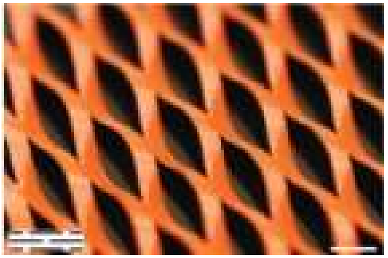
Muscles, Grippers, Logic, and Actuators

Douglas P. Holmes

Associate Professor
Mechanical Engineering
College of Engineering

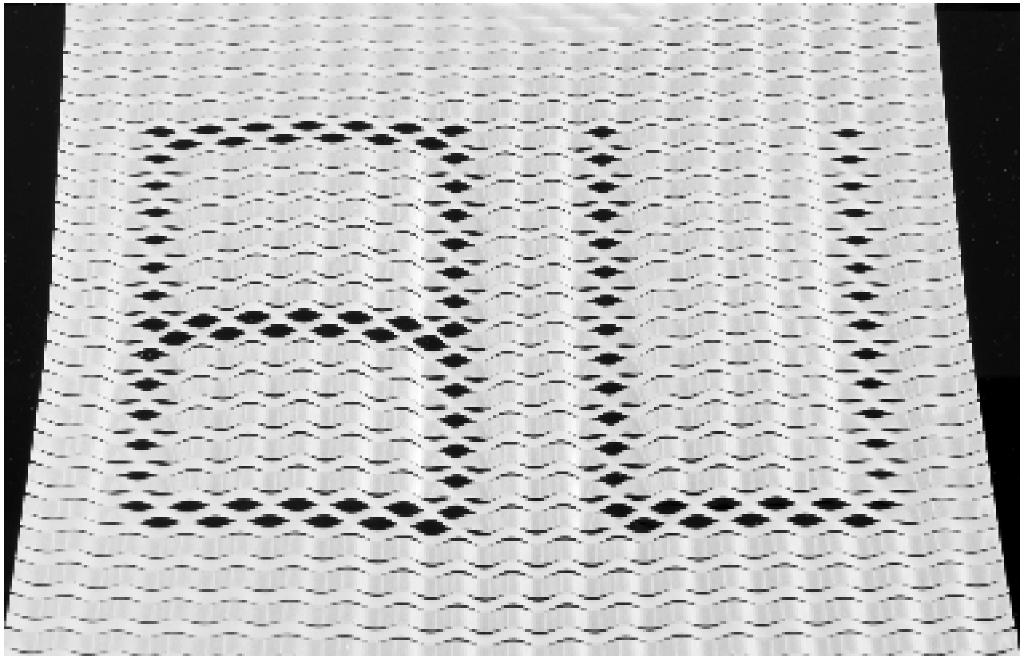
Cuts in a Sheet



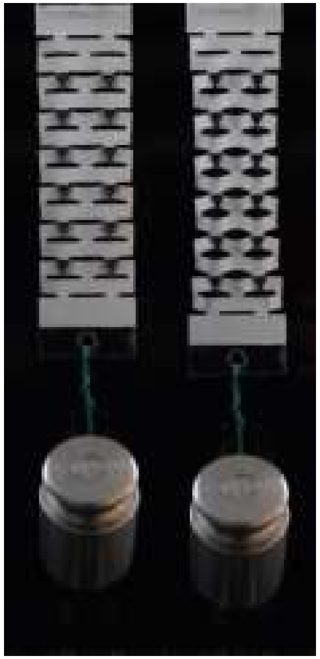


Increase Cut Spacing

Each unit cell is bistable



Switching changes the stiffness



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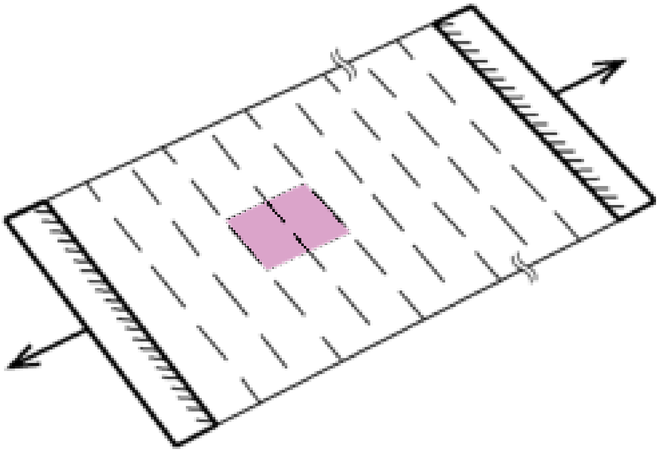
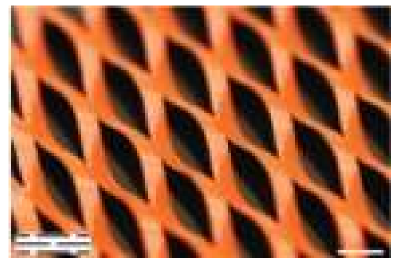
Y. Yang M.A. Dias, and D.P. Holmes, "Architected Materials with Tunable Properties using Multistable Kirigami," Physical Review Materials, 2, 110601(R), (2018).



Cuts in a Sheet



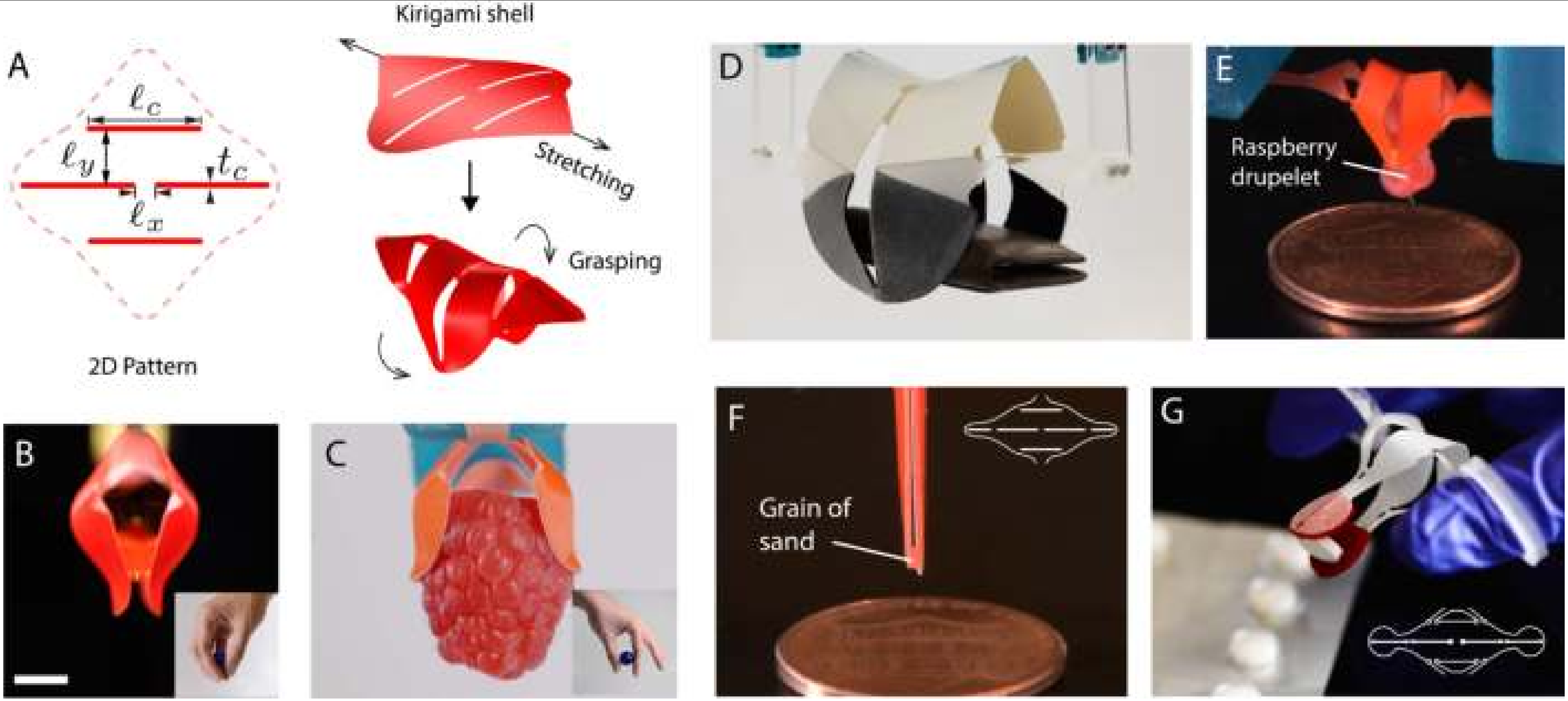
Increase Cut Spacing

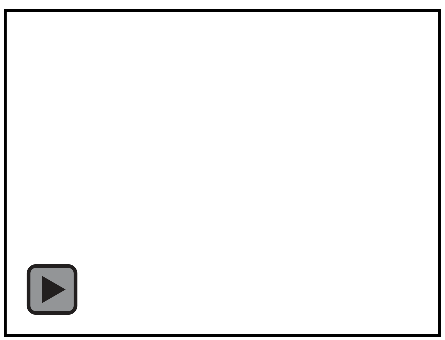
Add Curvature

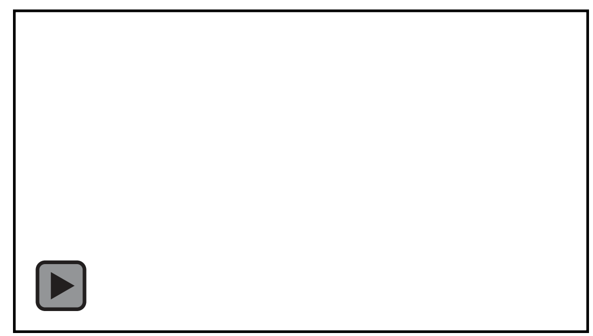
Grasping

Kirigami Gripper

Y. Yang, K. Vella, and D.P. Holmes, “Grasping with Kirigami Shells,” *Science Robotics*, 6, eabd6426, (2021).







Y. Yang, K. Vella, and D.P. Holmes, "Grasping with Kirigami Shells," *Science Robotics*, 6, eabd6426, (2021).

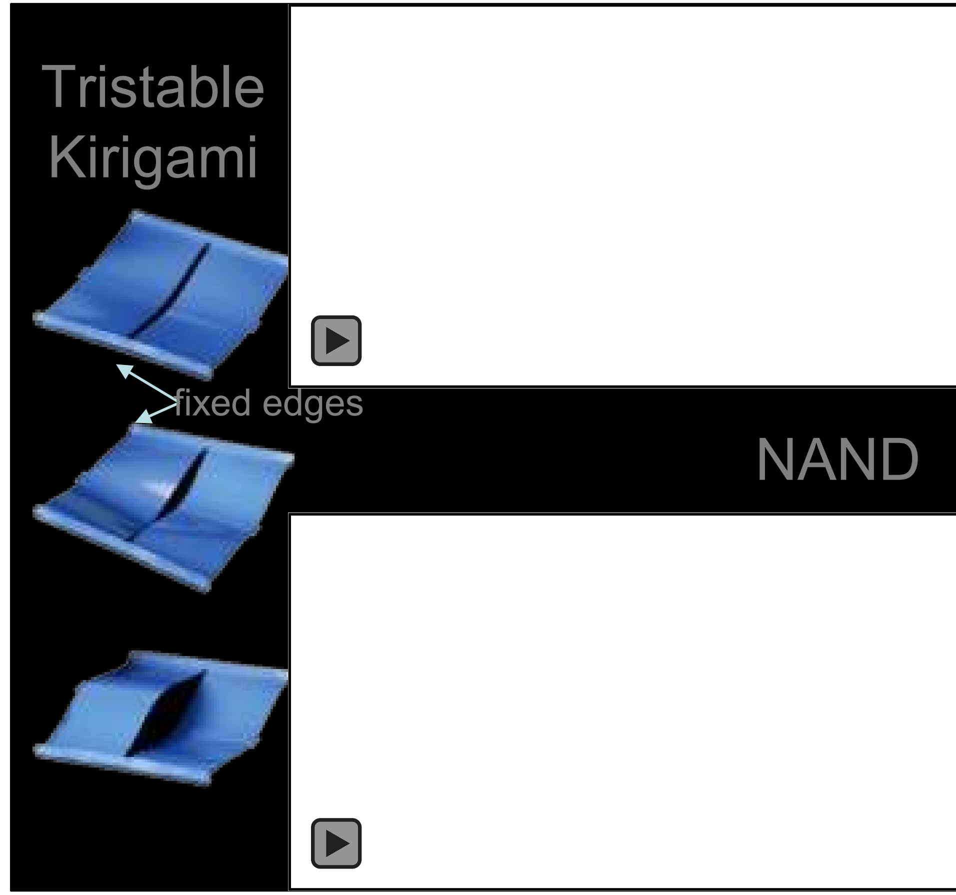
Linear Actuators

Pitch

Roll

M.A. Dias, M.P. McCarron, D. Rayneau–Kirkhope, P.Z. Hanakata, D.K. Campbell, H.S. Park, and D.P. Holmes, “Kirigami Actuators,” Soft Matter, 13, 9087–9092, (2017).

Mechanical Logic



Y. Yang, J. Feng, and D.P. Holmes, “Kirigami Logic,” *In Preparation, (2023)*.

Soft Robotic Exosuits For Post-Stroke Locomotor Recovery

Lou Awad, PT, DPT, PhD

Assistant Professor
Department of Physical Therapy
College of Health and Rehabilitation Sciences: Sargent

https://sites.bu.edu/**NRL**
louawad@bu.edu

< 3500 steps per day of physical activity

Poor health and reduced quality of life

A New Paradigm: Soft Robotic Exosuits For Assistance & Rehabilitation

A New Paradigm: Soft Robotic Exosuits For Assistance & Rehabilitation

Awad et al. A soft robotic exosuit improves walking after stroke. *Science Translational Medicine*. 2017

Awad et al. Reducing circumduction and hip hiking during hemiparetic walking with a soft robotic exosuit. *Amer J Phys Med Rehab*. 2017

Awad et al. Walking faster and farther with a soft robotic exosuit: Implications for post-stroke gait assistance and rehabilitation. *IEEE OJEMB*. 2020

Awad et al. These legs were made for propulsion: Advancing the diagnosis and treatment of post-stroke propulsion deficits. *J NeuroEngineering & Rehab*. 2020

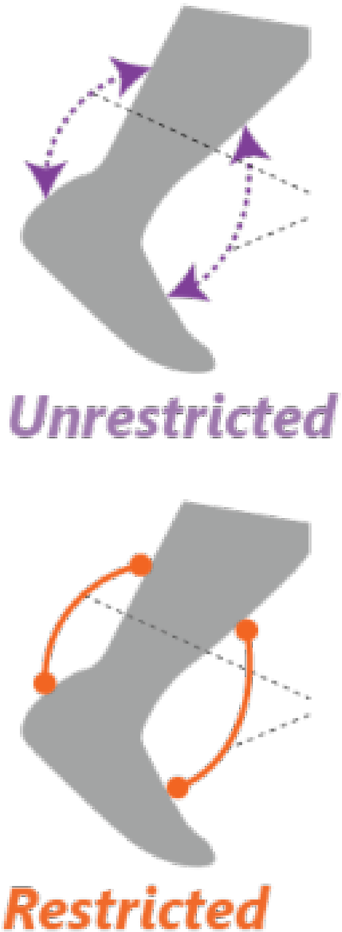
Sloutsky et al. Targeting post-stroke walking automaticity with a propulsion-augmented soft robotic exosuit. *IEEE Conf Neural Engineering*. 2021

Porciuncula et al. Targeting paretic propulsion and walking speed with a soft robotic exosuit: A consideration-of-concept trial. *Frontiers Neurorobotics*. 2021

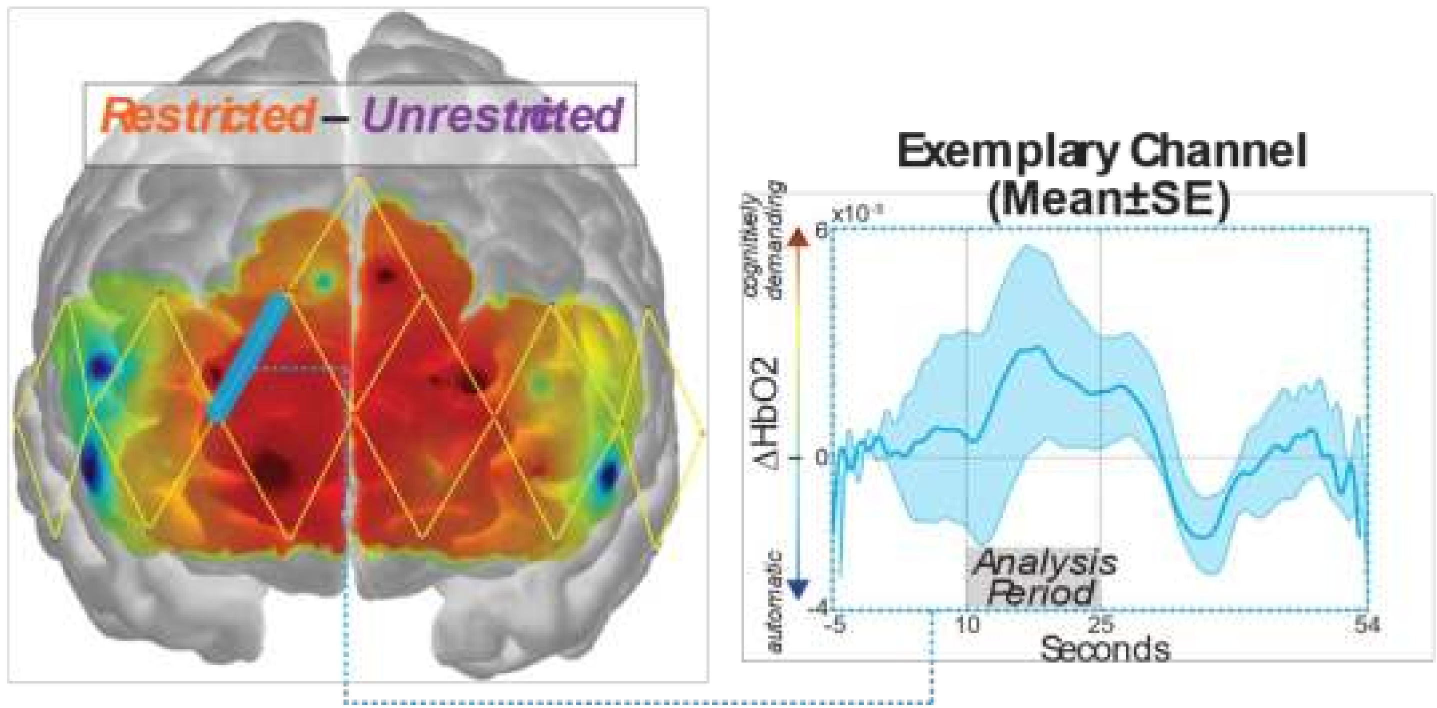
Roto et al. Enhancing neuroplasticity after stroke: Effects of a soft robotic exosuit on exercise intensity and brain-derived neurotrophic factor. *IEEE OJEMB*. 2023

Exosuits *supplement* the work (and thinking)

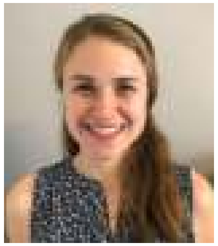
Exosuits *supplement* the work (and thinking)



Walking with a mismatched exosuit…

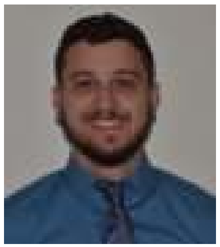


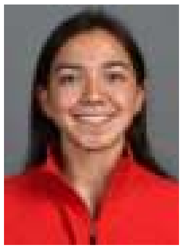

Franchino Porciuncula (Research Scientist)


Johanna Spangler (Research PT)

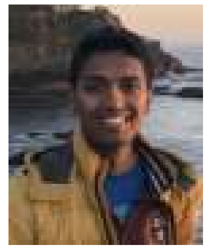

Teresa Baker (Research PT)


Karen Hutchinson (Clinical Faculty)


Andre Alvarez (PhD student)

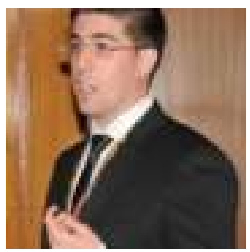

Ashlyn Aiello (PhD student)


Regina Sloutsky (PhD student)


Dheepak Arumukhom Revi (PhD Student)


Ashley Collimore (PhD student)


Anna Roto (PhD Student)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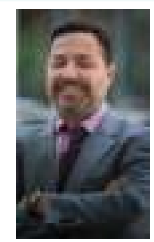
Dave Sherman (Postdoc)

Neuromotor Recovery Laboratory

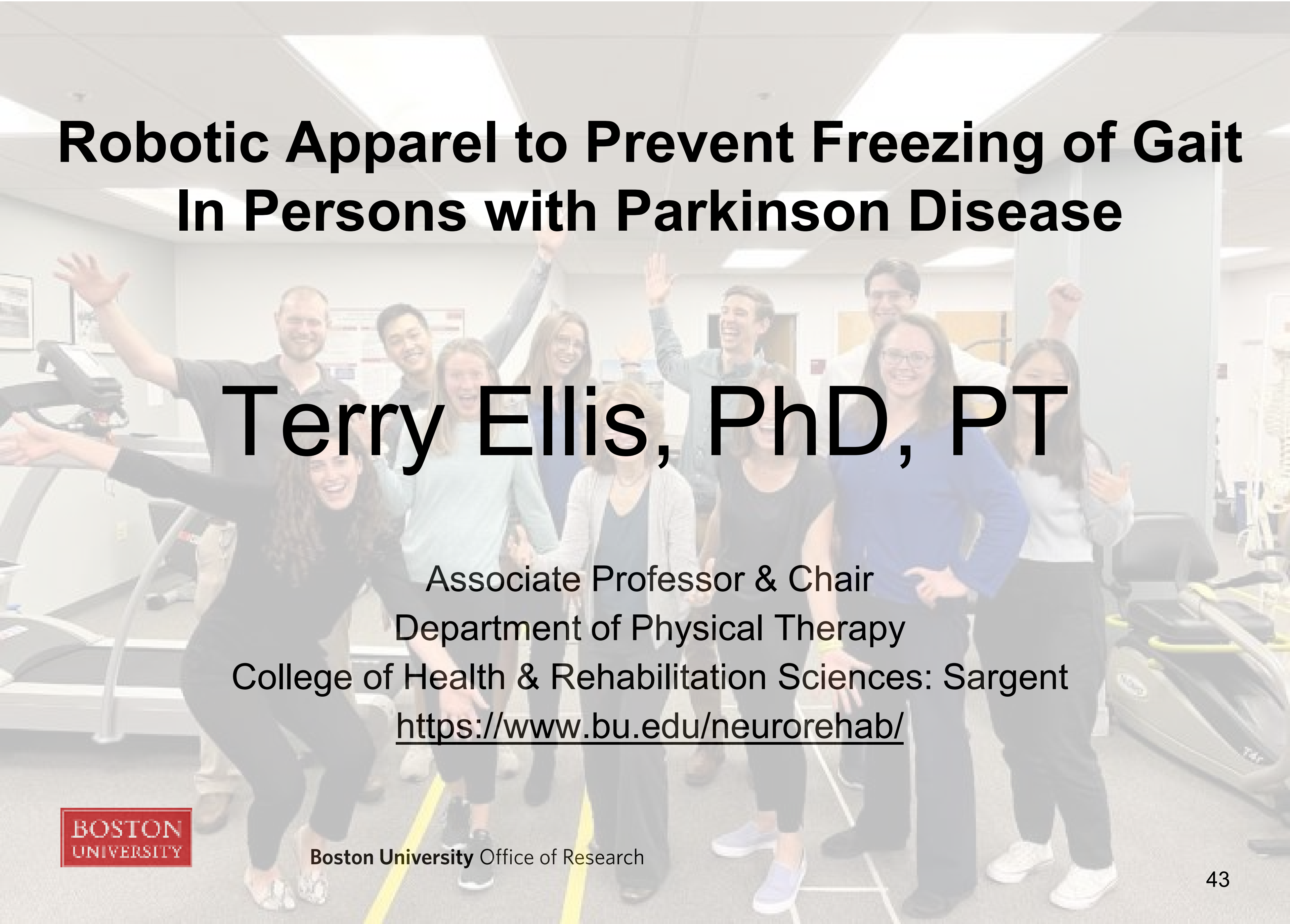

Terry Ellis


Conor Walsh


Paolo Bonato


Joan Breen

Boston University | Massachusetts Technology Collaborative | American Heart Association | NIH | NSF | ReWalk More Than Walking | Harvard Move Lab

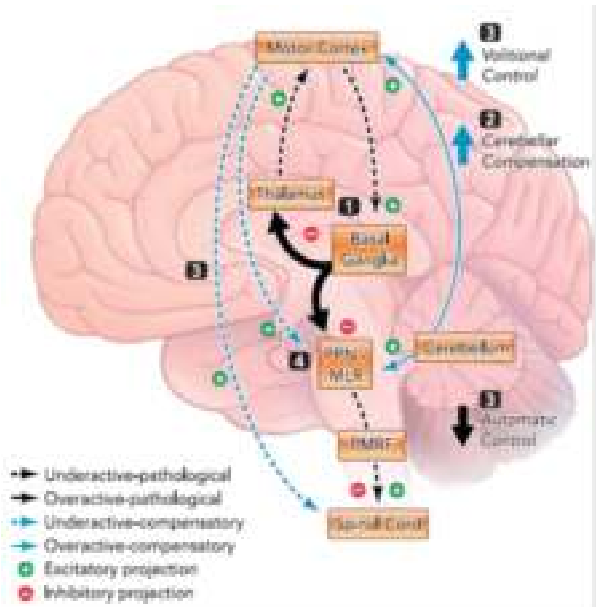


Robotic Apparel to Prevent Freezing of Gait In Persons with Parkinson Disease

Terry Ellis, PhD, PT

Associate Professor & Chair
Department of Physical Therapy
College of Health & Rehabilitation Sciences: Sargent
https://www.bu.edu/neurorehab/

Freezing of gait (FOG) is a brief episodic absence or marked reduction in forward progression of the feet despite the intention to walk.



Loss of walking automaticity

Peterson, 2016

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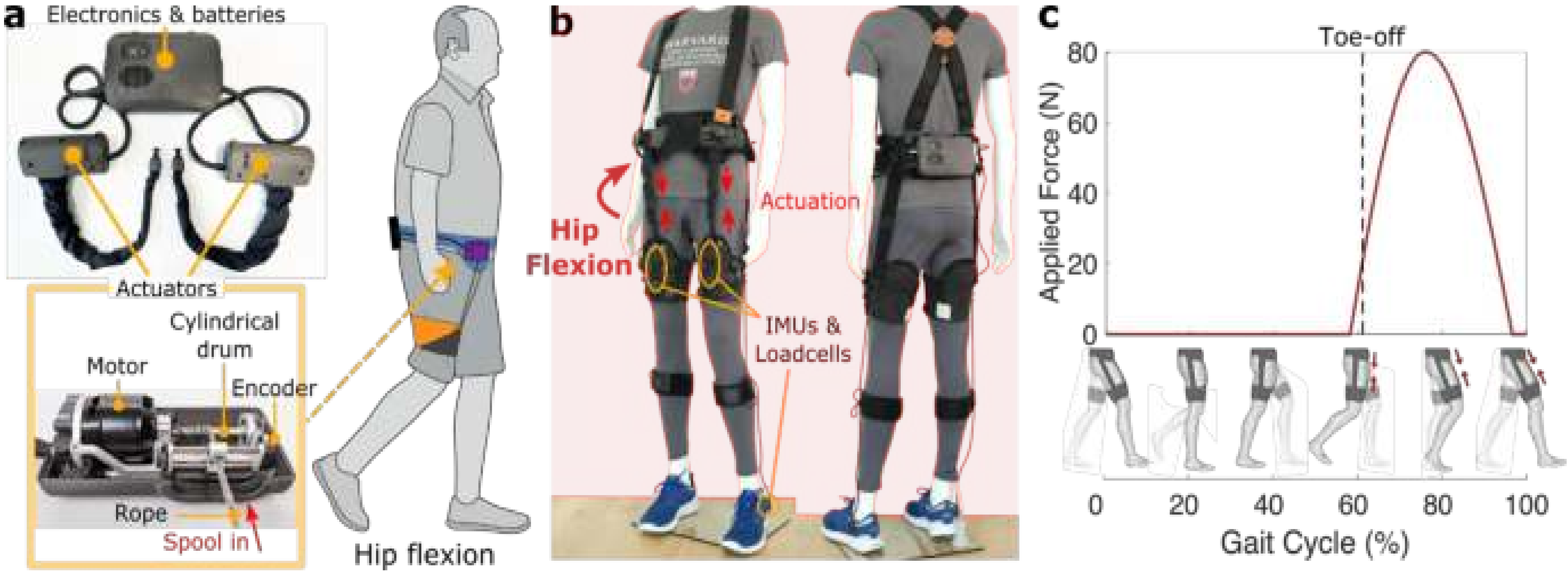
Soft Robotic Hip Flexor System



Duration of FOG

40% “time spent frozen” with exosuit “off”
0 episodes of FOG with exosuit “on”

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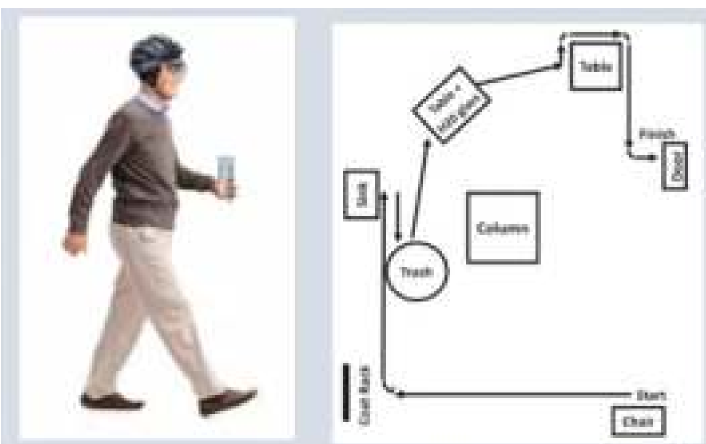
Clinical Outcomes & Next Steps

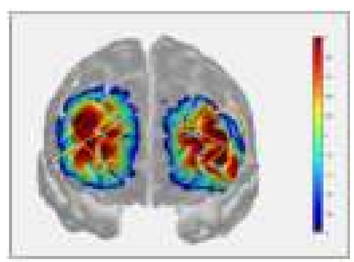
Future….

With the Exosuit powered "on":

- Faster gait speed
- Longer distance walking
- Longer step lengths



Improving walking automaticity?



Thank You Collaborators & Center for Neurorehabilitation Team

Conor Walsh, PhD
Harvard University

Lou Awad, PT, PhD
Boston University

Franchino Porciuncula, PT, DScPT, EdD
Boston University

Jinsoo Kim, PhD
Harvard University

Tim Nordahl, PT, DPT, NCS
Boston University

Nicholas Wendel, PT, DPT, NCS
Boston University

Teresa Baker, PT, DPT, NCS
Boston University

Ludy Shih, MD
Department of Neurology
BUMC

Interactive Autonomy at Scale

Eshed Ohn-Bar

Assistant Professor
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College of Engineering
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mobility@bu.edu

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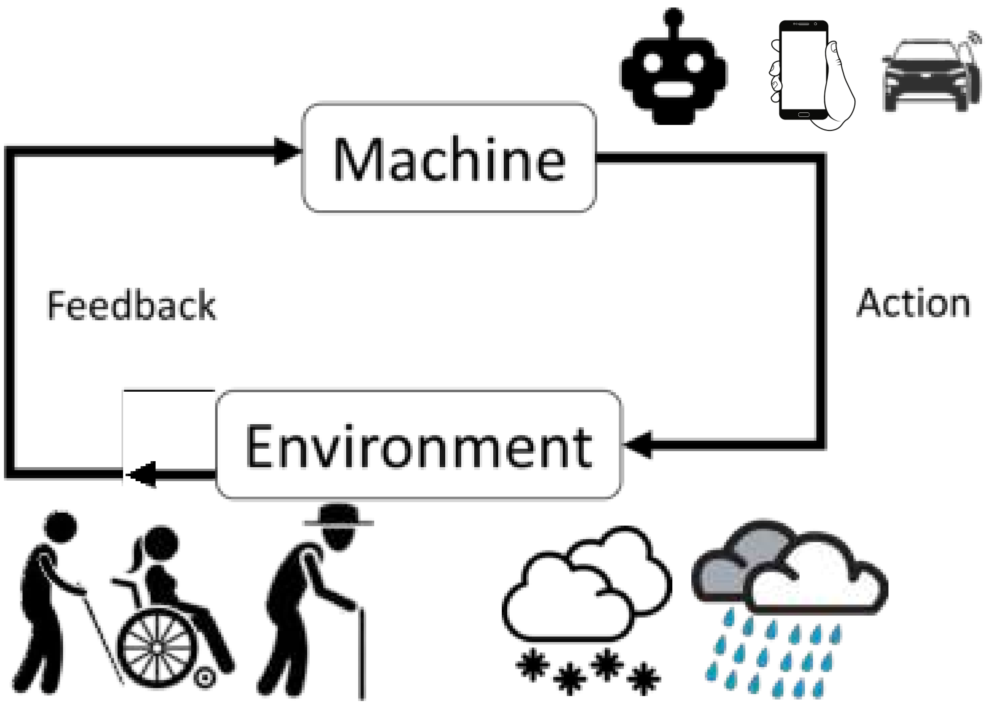
Boston University Office of Research

H2X Lab

Why? Seamless Interaction

Main Tool: *M*achine learning with feedback and real-world data for *perception-cognition-action systems*



Personalized Assistive Systems

Robust Perception & Autonomy

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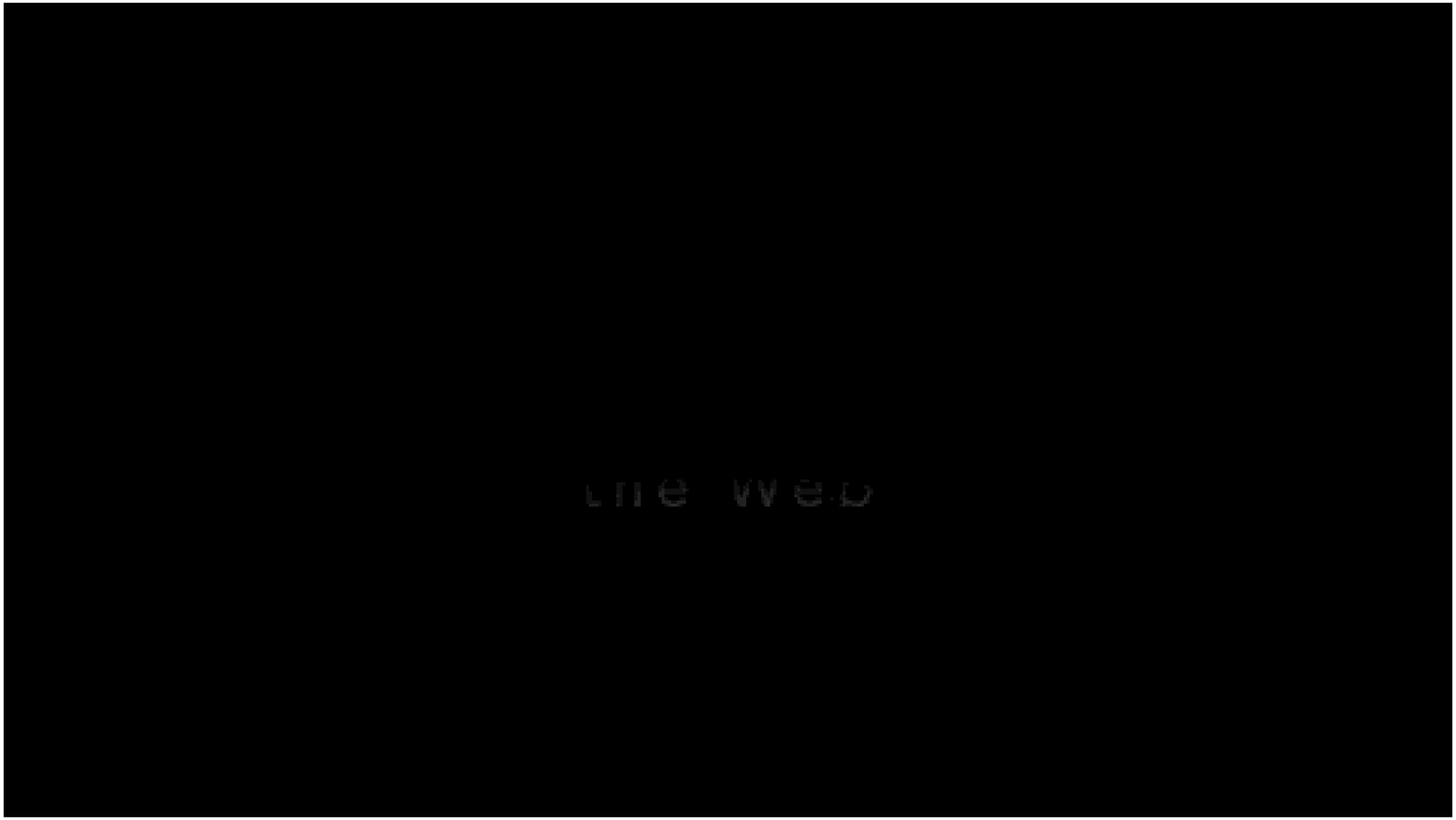
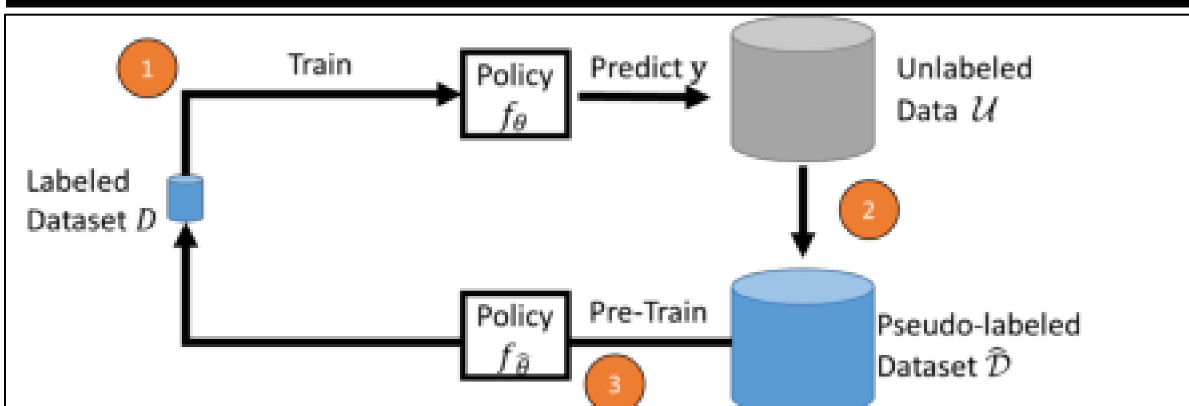
Boston University Office of Research

Motional

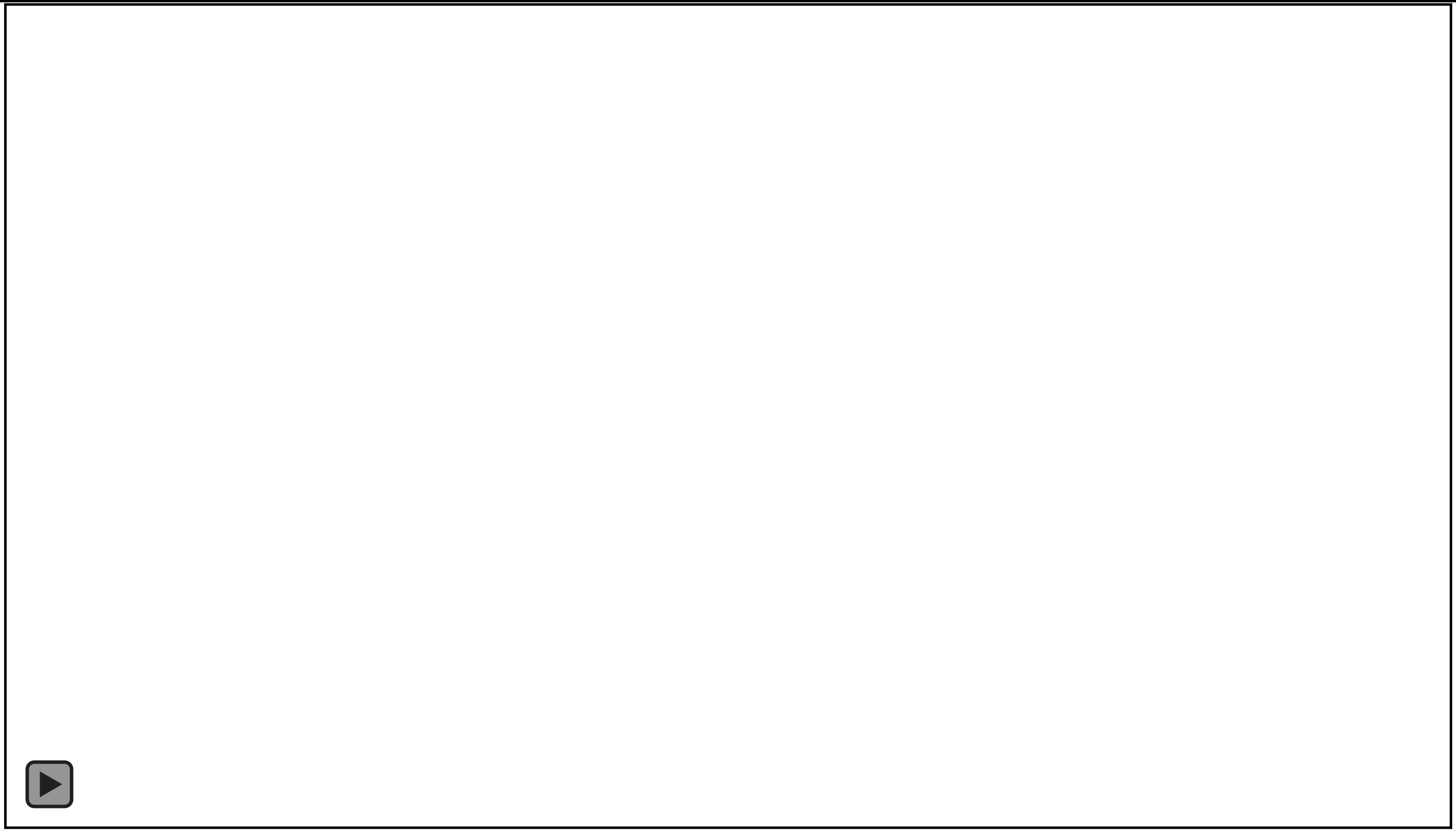
Leveraging Vast Amounts of Freely Available Data for 20% Better Driving

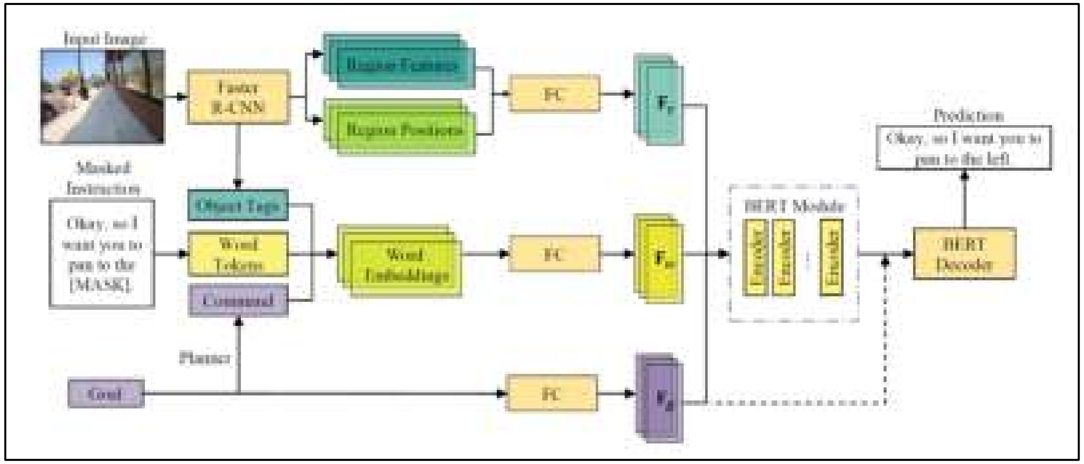




Zhang, Zhu & Ohn-Bar, CVPR 2022

Goal-Driven Personalized Assistive Policies





Huang, Shangguan, Zhang, Bar, Boyd & Ohn-Bar, ASSISTER, ECCV 2022

Towards Seamless Interaction in the Real-World

On-Going Research

- Coupling **high-dimensional perception** input with interaction and assistance under hard real-time safety constraints.
- Usability and **customization** for users and settings.

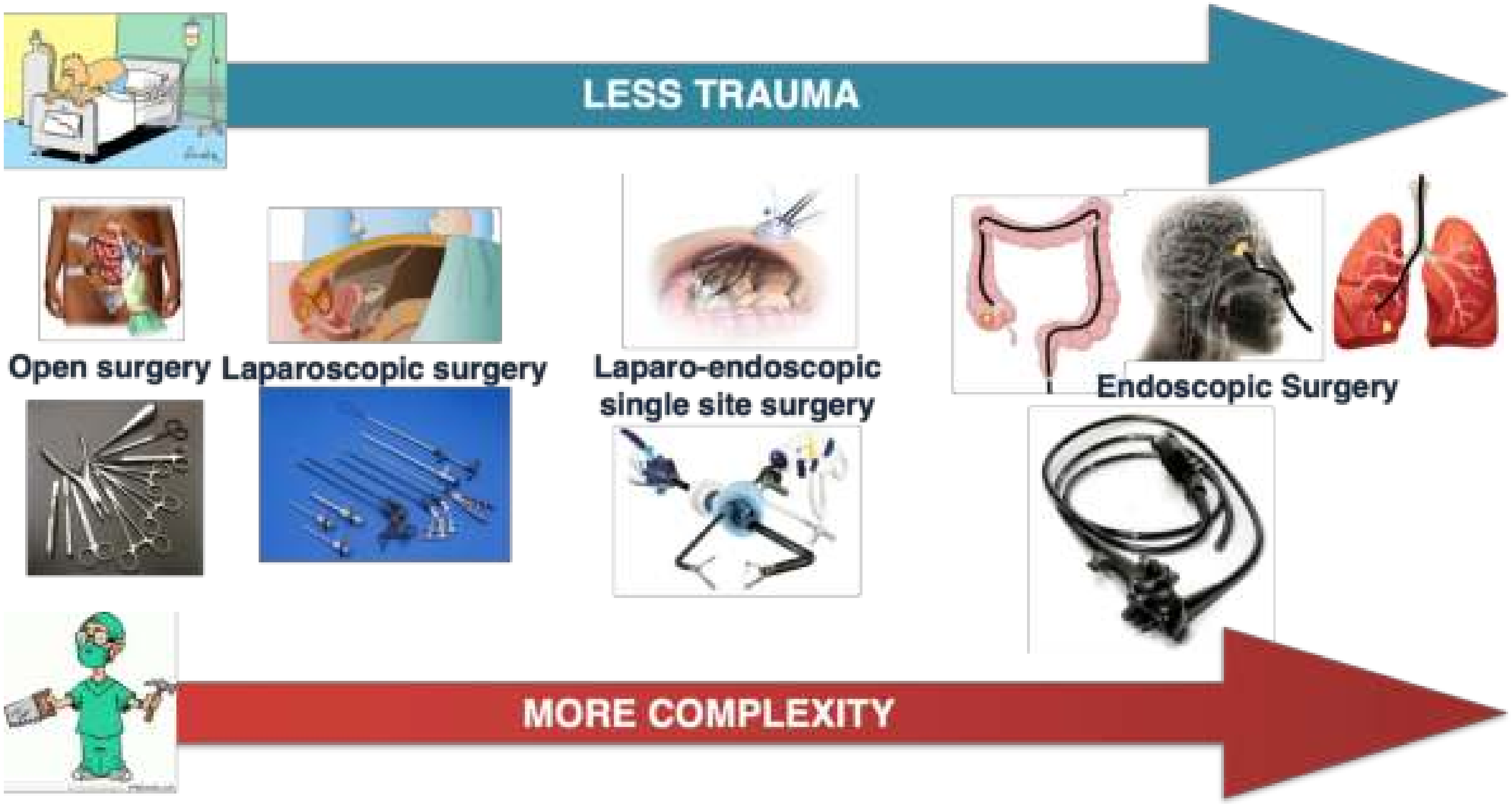
Soft Material Robotics and Next-Generation Surgical Robots

Sheila Russo, Ph.D.

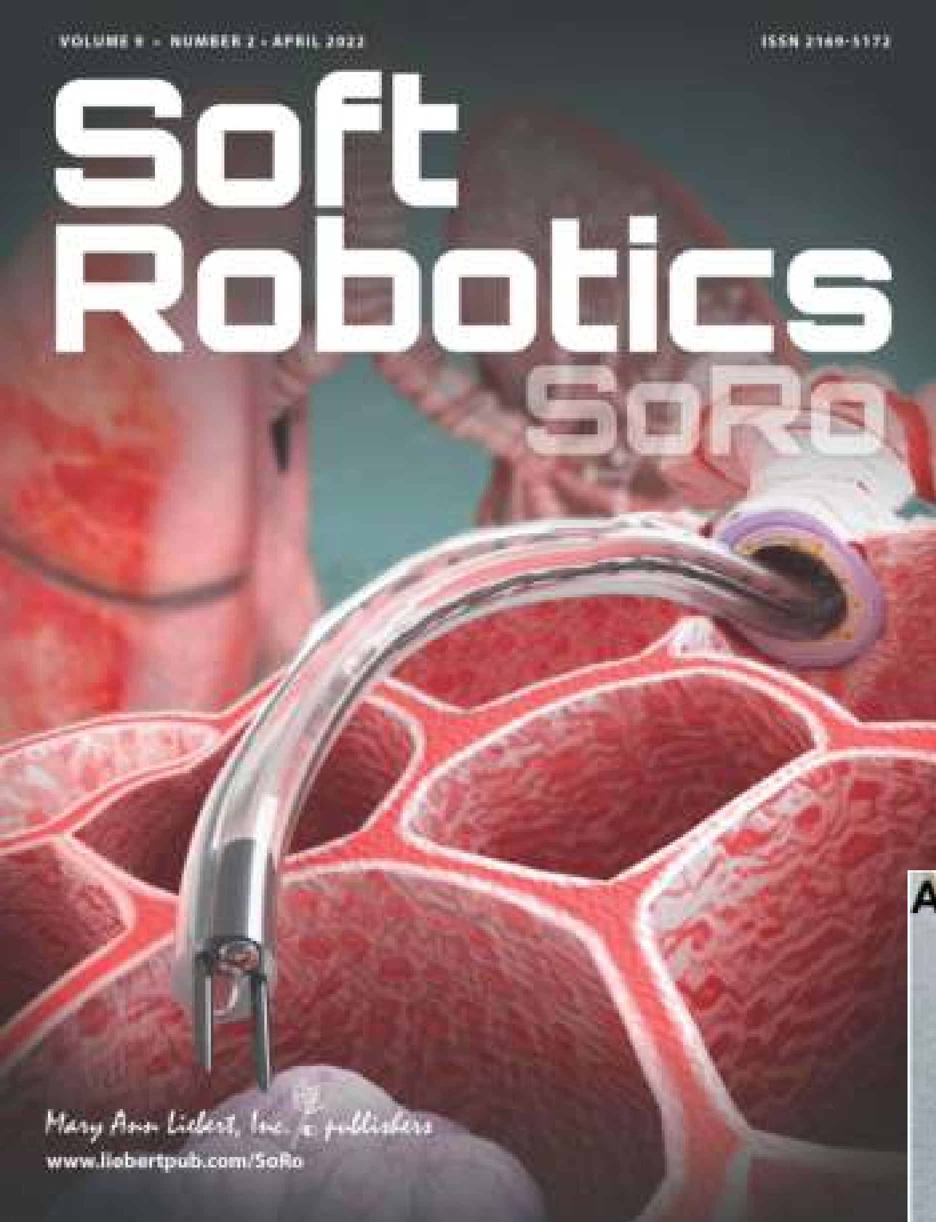
Assistant Professor
Material Robotics Lab
Department of Mechanical Engineering
Division of Materials Science & Engineering
College of Engineering

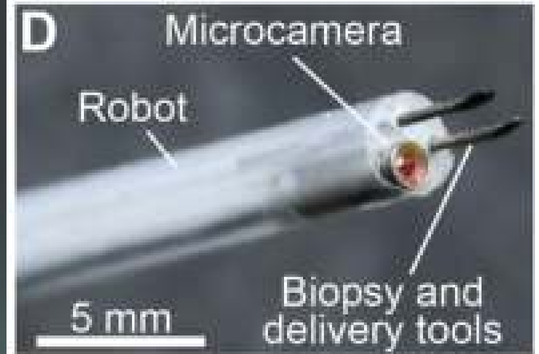
Open ***societal*** challenges and unsolved ***robotics*** challenges

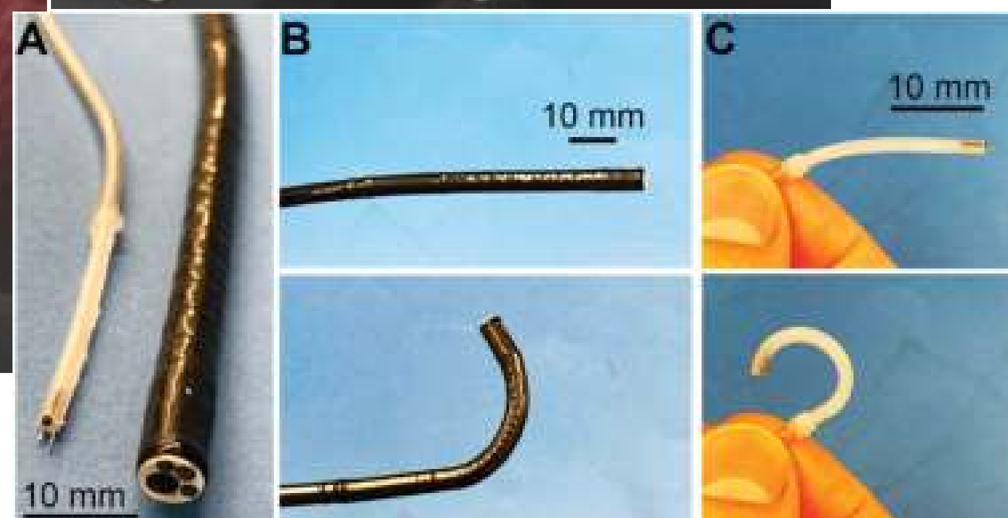
Q1: How do we guarantee **high-quality healthcare**?
Q2: How do we address **healthcare inequality**?



Q2: How can robots **navigate** in a complex and unstructured environment?
Q3: How can robots **manipulate** fragile and delicate objects?
Q4: How can robots achieve *safe* distal **actuation**, integrated **sensing**, articulation, and effective **force transmission** while in *close* contact with humans?







Funding:

Johnson & Johnson

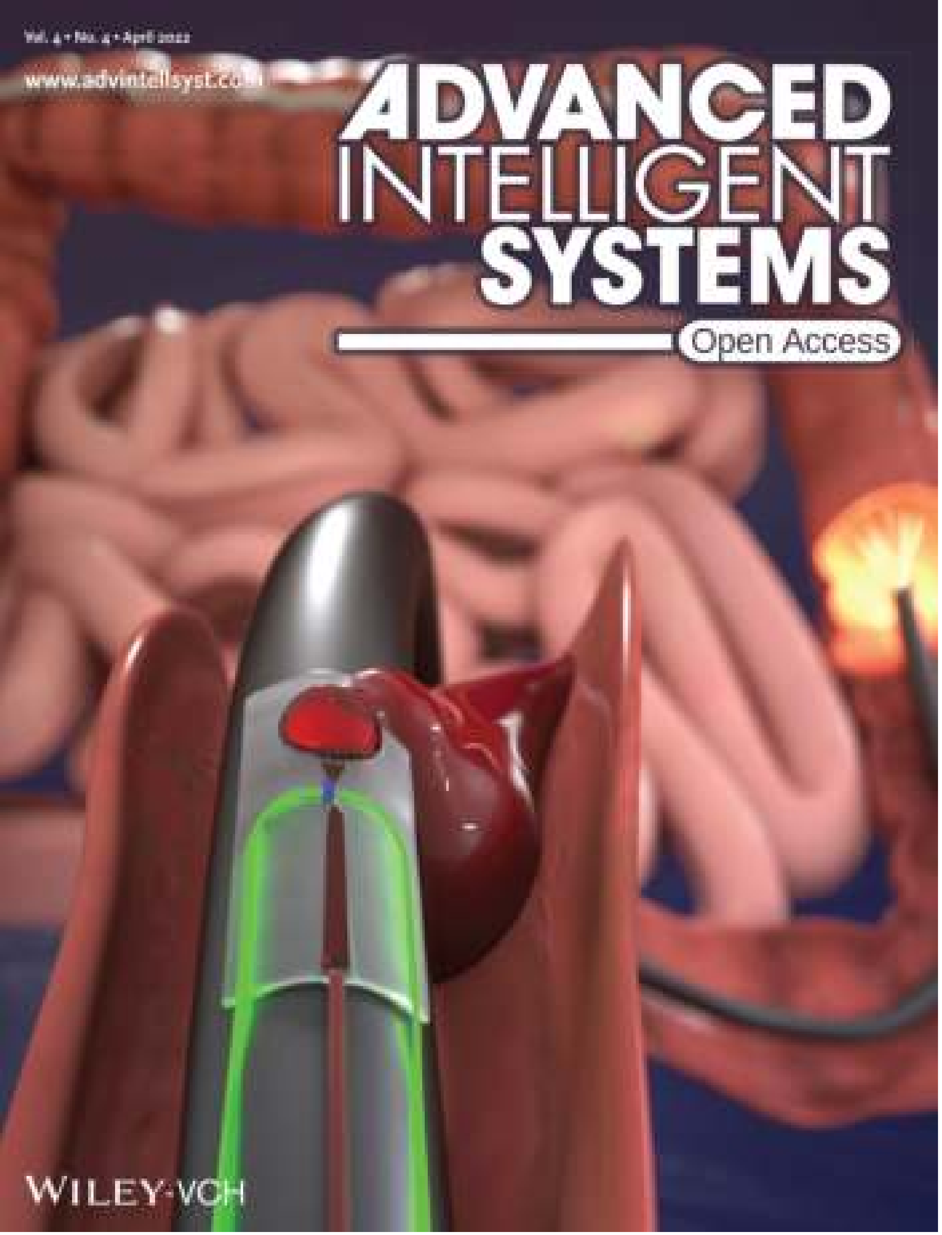
BU CTSI

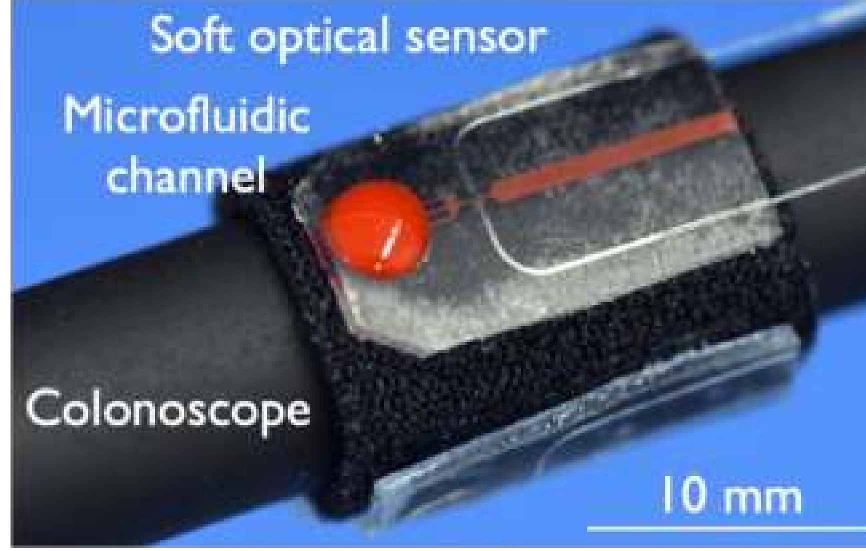
NIH

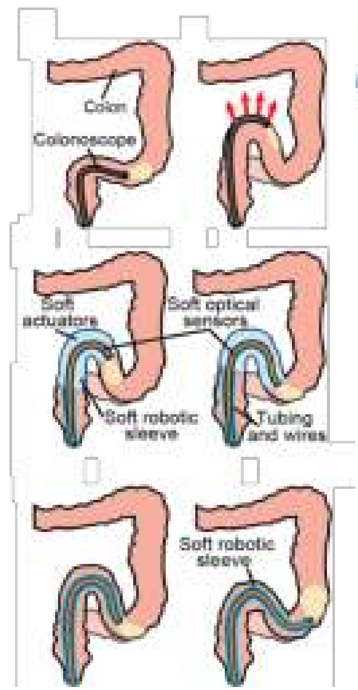
Collaborators: Boston Medical Center

EXCEPTIONAL CARE. WITHOUT EXCEPTION.

McCandless M., Perry A., DiFilippo N., Carroll A., Billatos E., Russo S., *Soft Robotics*, 2021.
Van Lewen D., Janke T., Lee H., Austin R., Billatos E., Russo S., *Advanced Intelligent Systems*, 2023.



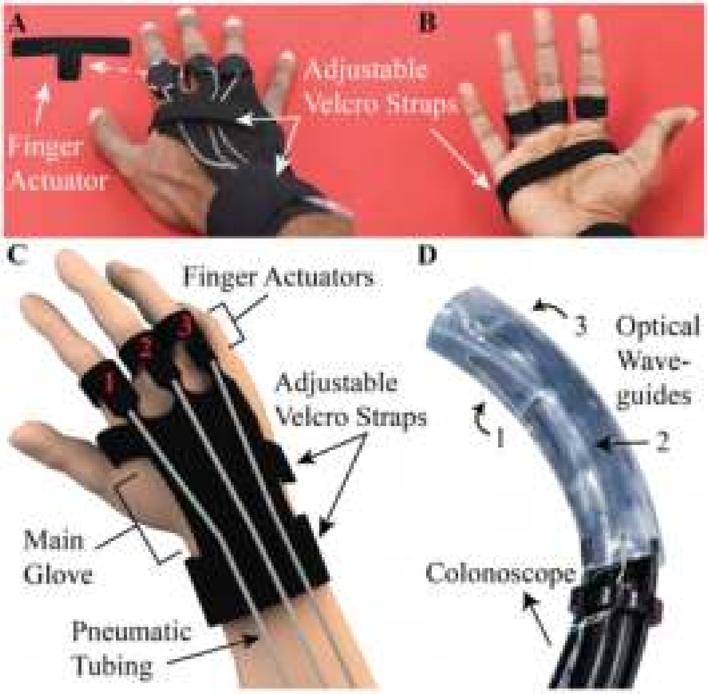




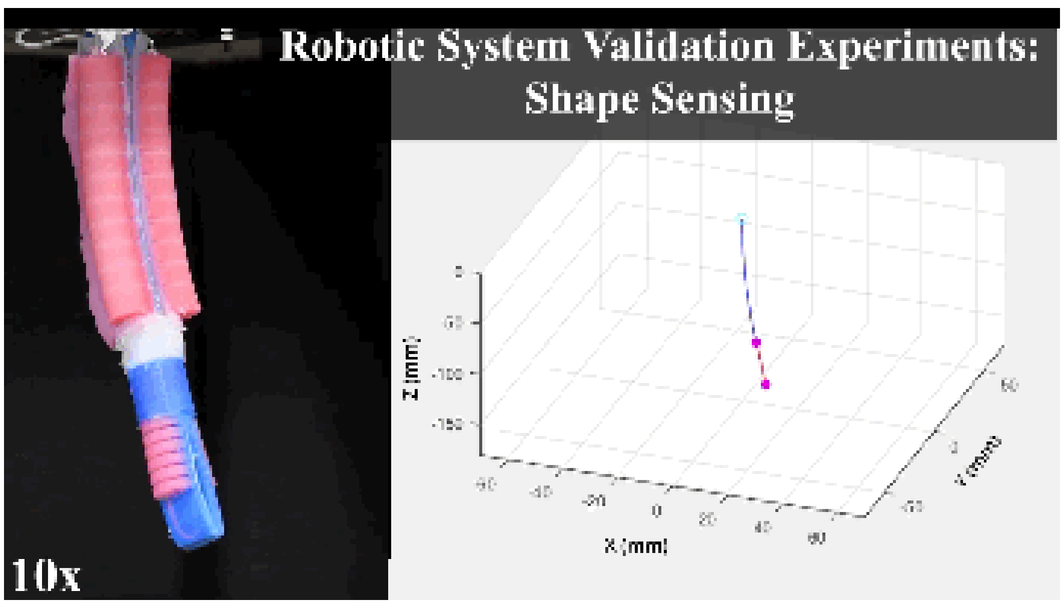
Collaborators: BWH HARVARD MEDICAL SCHOOL

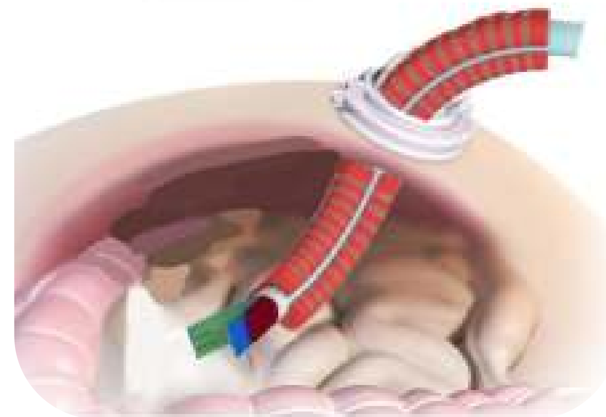
Funding: NIH National Institute of Biomedical Imaging and Bioengineering

McCandless M., Gerald A., Carroll A., Aihara H., and Russo S., “A Soft Robotic Sleeve for Safer Colonoscopy Procedures”, *IEEE Robotics and Automation Letters*, 2021.
Gerald A., McCandless M., Sheth A., Aihara H., and Russo S., “A Soft Sensor for Bleeding Detection in Colonoscopies”, *Advanced Intelligent Systems*, 2022.



Clinical Evaluation





Collaborators:

BWH HARVARD MEDICAL SCHOOL

Funding:

NIH National Institute of Biomedical Imaging and Bioengineering

Gerald, A., Batliwala, R., Ye, J., Hsu, P., Aihara, H. and Russo, S., 2022, October. A Soft Robotic Haptic Feedback Glove for Colonoscopy Procedures. In *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (pp. 583-590). IEEE.
McCandless, M., Wise, and Russo, S., 2023. A Soft Robot with Three Dimensional Shape Sensing and Contact Recognition Multi-Modal Sensing via Tunable Soft Optical Sensors. In *2023 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE.

MBL
Morphable Biorobotics Lab

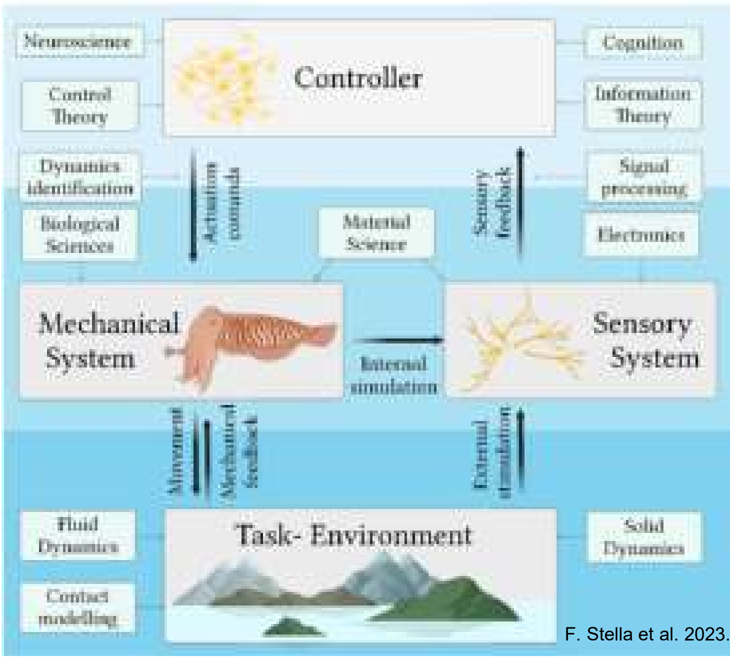
Enabling Robots to Function in Complex and Unstructured Environments

Tom Ranzani

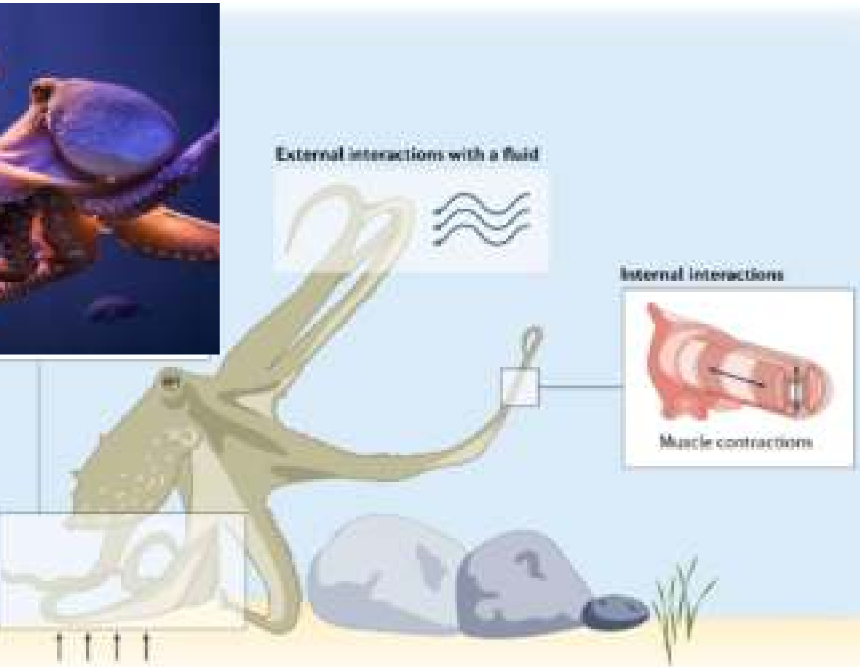
Assistant Professor
Department of Mechanical Engineering
Department of Biomedical Engineering
Material Science & Engineering Division
College of Engineering

High predictability
Programmability

Low predictability
Uncertainty



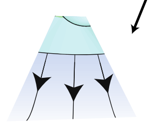
F. Stella et al. 2023.



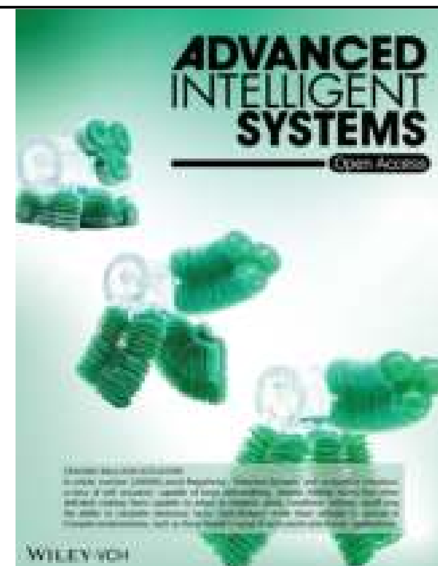
How do we replicate complexity of biological systems into artificial devices? How can we control and leverage such complexity to operate in unstructured environments?

a)

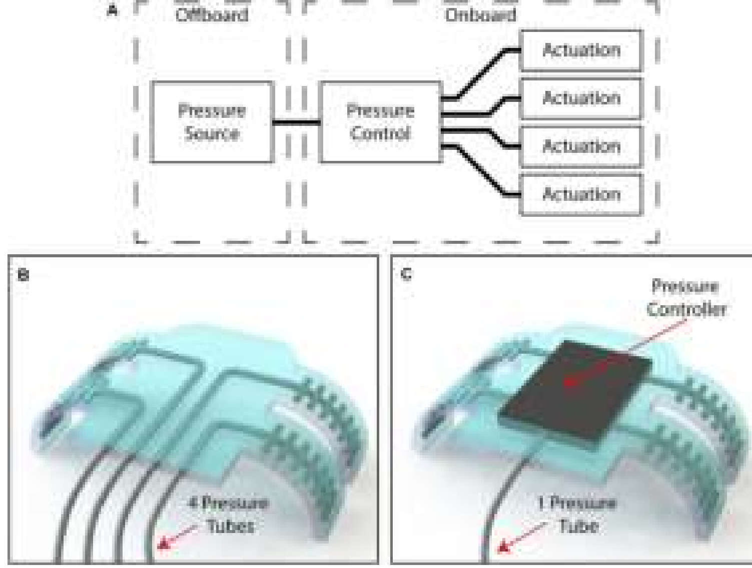
b)

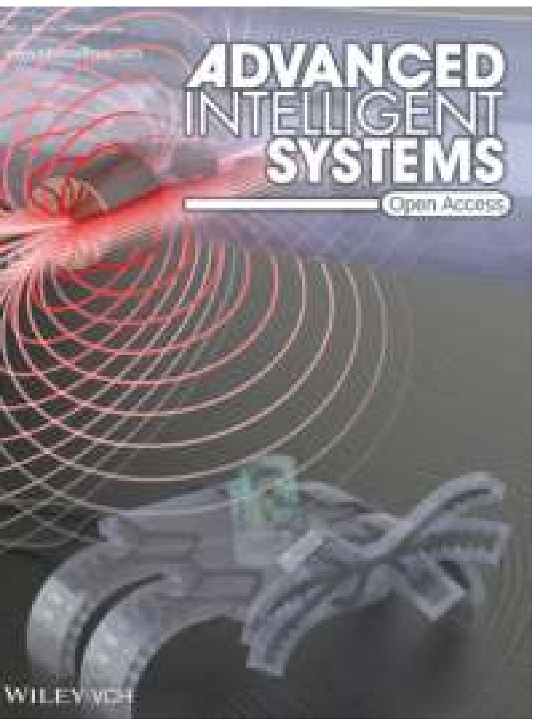


c)



J. Rogatinsky *et al.*, “A Collapsible Soft Actuator Facilitates Performance in Constrained Environments,” *Adv. Intell. Syst.*, vol. 2200085, p. 2200085, Jun. 2022

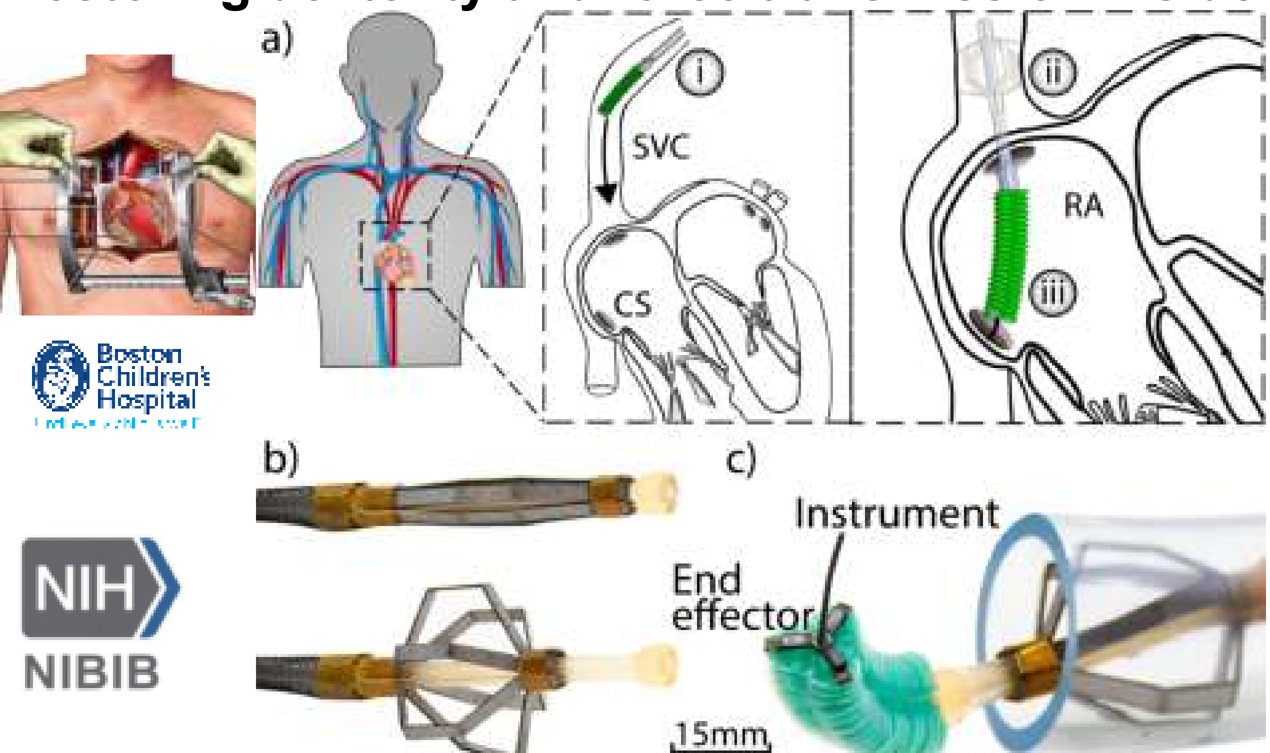




K. McDonald, L. Kinnicutt, A. M. Moran, and T. Ranzani, “Modulation of Magnetorheological Fluid Flow in Soft Robots Using Electropermanent Magnets,” *IEEE Robot. Autom. Lett.*, vol. 3766, no. c, pp. 1–1, 2022.
K. McDonald and T. Ranzani, “Hardware Methods for Onboard Control of Fluidically Actuated Soft Robots,” *Front. Robot. AI*, vol. 8, Aug. 2021.
K. McDonald, A. Rendos, S. Woodman, K. A. Brown, and T. Ranzani, “Magnetorheological Fluid-Based Flow Control for Soft Robots,” *Adv. Intell. Syst.*, p. 2000139, Sep. 2020.

Safe and effective manipulation of large abdominal organs

Restoring dexterity and force transmission inside the beating heart



Thanks!

Morphable Biorobotics lab research areas:

- Soft Robotics
- Bioinspired robotics
- Surgical robotics
- Wearable robotics
- Soft Robot Control
- Variable stiffening mechanisms
- Sensing and Actuation

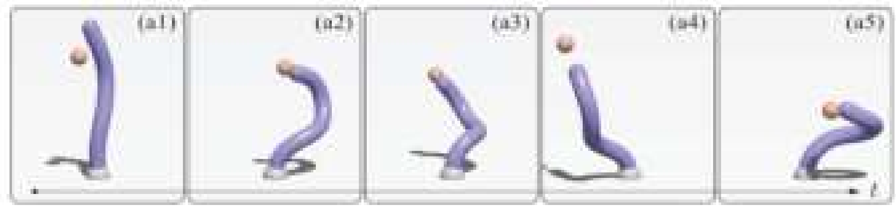
NIH NIBIB
BU CTSI
Office of Naval Research Science & Technology ONR

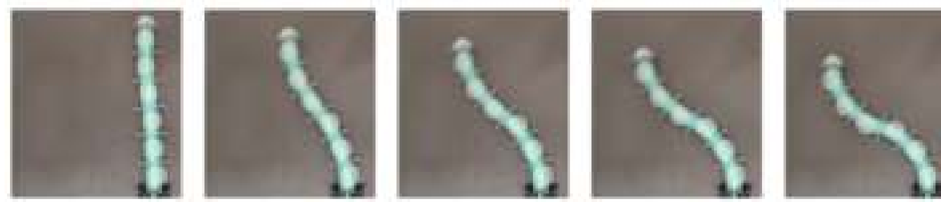
Controlling Soft Robots: Not as Hard as You'd Think

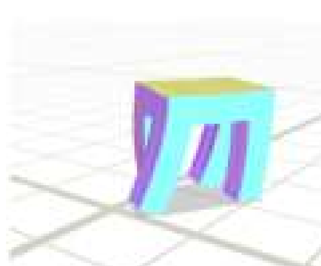
Andrew Sabelhaus

Assistant Professor
Mechanical Engineering, Systems Engineering
College of Engineering

Different challenges for traditional robots vs. soft robots





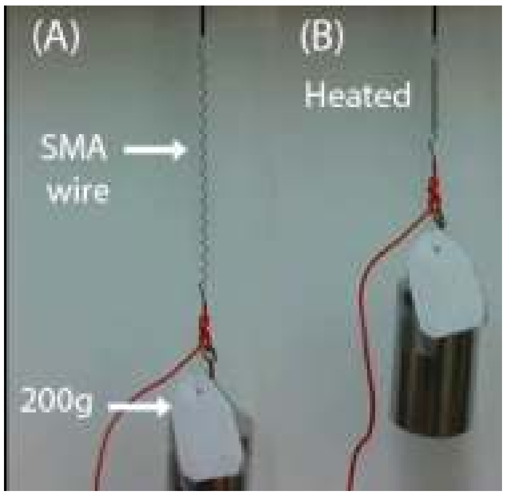


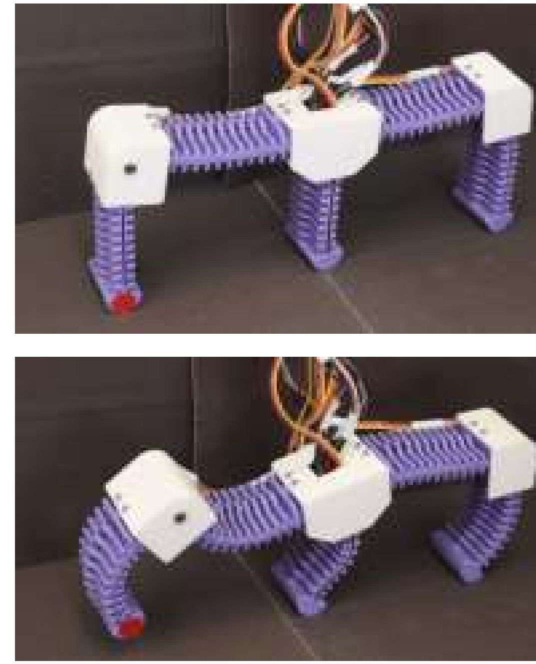
→ *Soft Robotics Control Lab*

Soft robot control: work with, not against!

First, design for control (and simulation):

Shape Memory Alloy, Discrete Elastic Rods

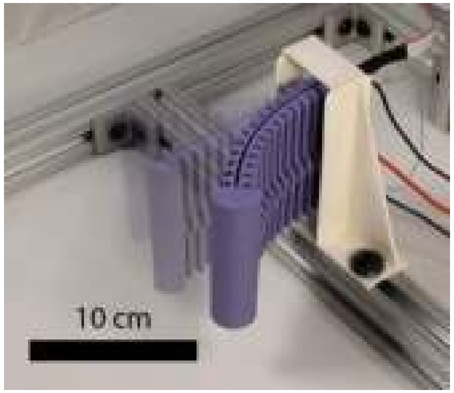


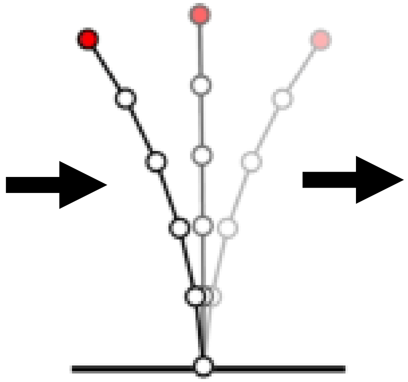


Jing et al., *arXiv:2209.13715,* 2022, **Sabelhaus** et al., *Frontiers in Robotics and AI,* 2022

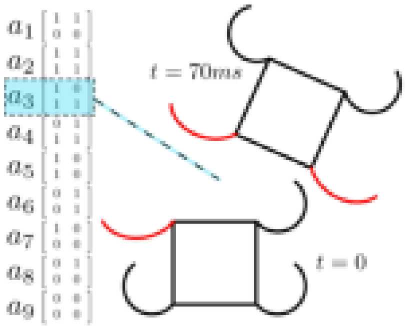
Then, for simpler tasks…

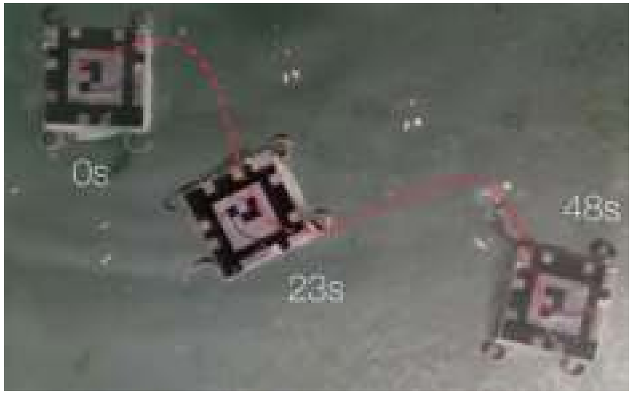
Approximation as a rigid robot, “Teach and Repeat”

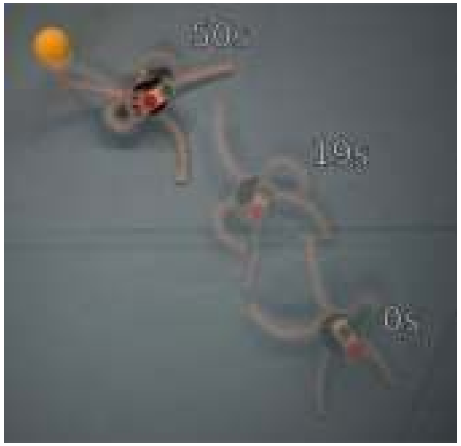




Planning over precalculated actions





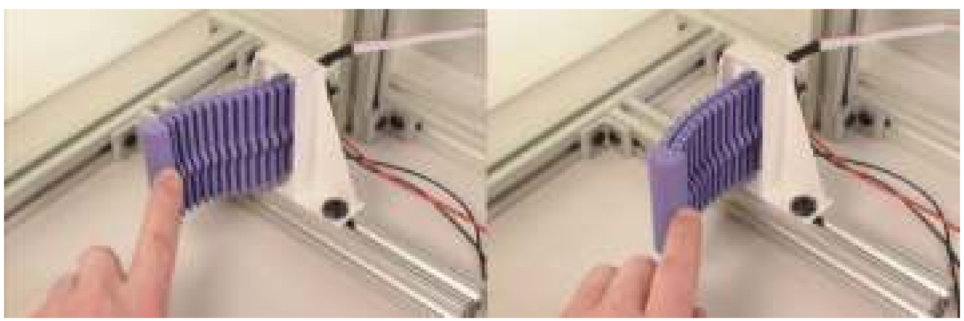


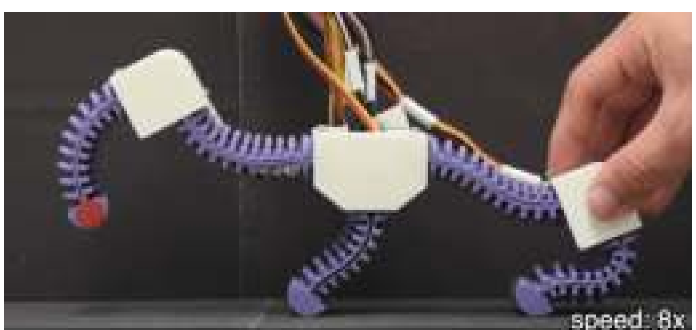
Wertz*, **Sabelhaus*,** Majidi, *IEEE Int. Conf. Soft Robotics*, 2022 Huang **et al.**, *Advanced Intelligent Systems*, 2022

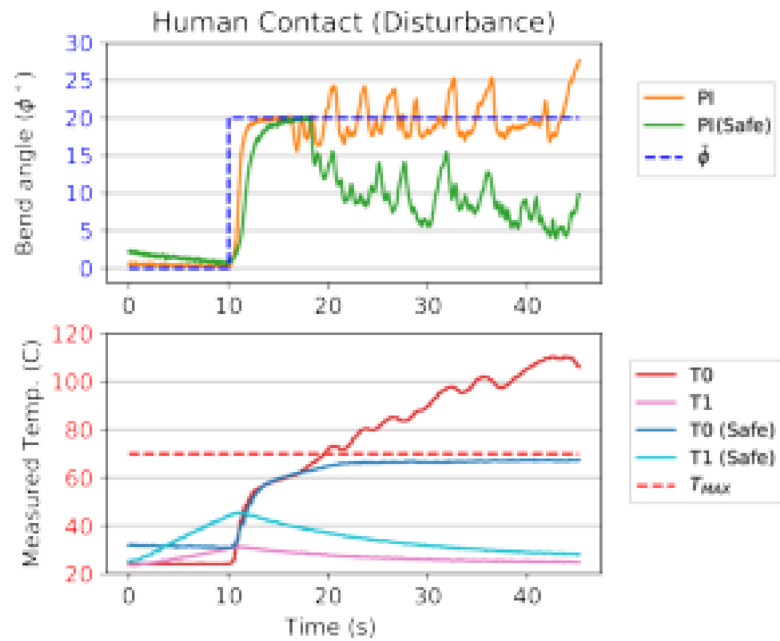
When the robot touches its surroundings…

Robustness to model uncertainty and disturbances

Verifiable safety with set invariance







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Patterson, **Sabelhaus*,** Majidi, *IEEE Rob. Aut. Letters*, 2022

Sabelhaus et al., *arXiv:2208.01547*, 2022

Control for Sensing and Estimation

Sean Andersson

Professor
Mechanical Engineering
Systems Engineering
College of Engineering

BOSTON UNIVERSITY

biophysics

multi-agent systems

control for sensing and estimation

motion planning and exploration

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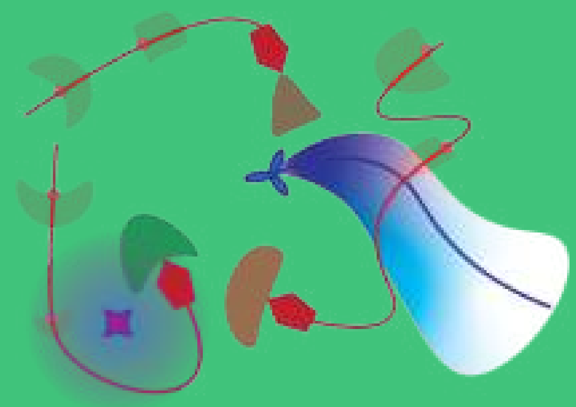
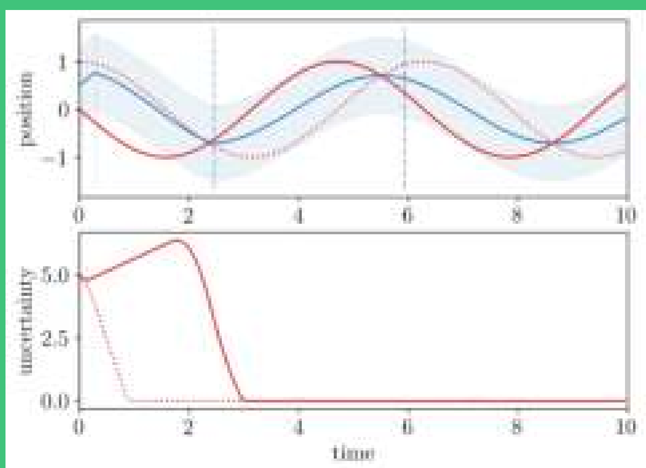
Multi-agent systems

Persistent monitoring





Data harvesting

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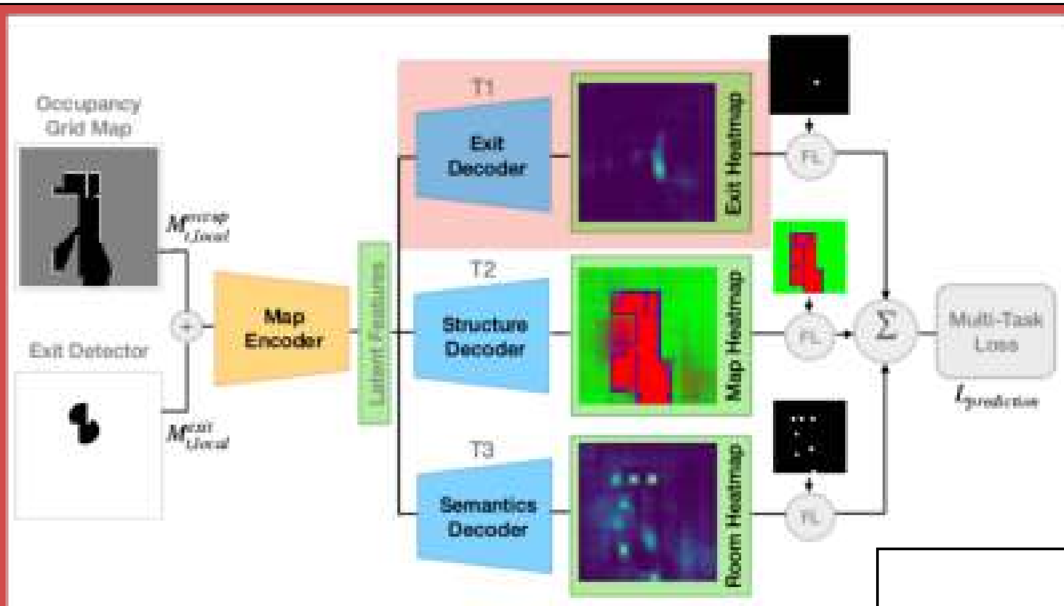
Collaboration with C. Cassandras

Motion planning and exploration



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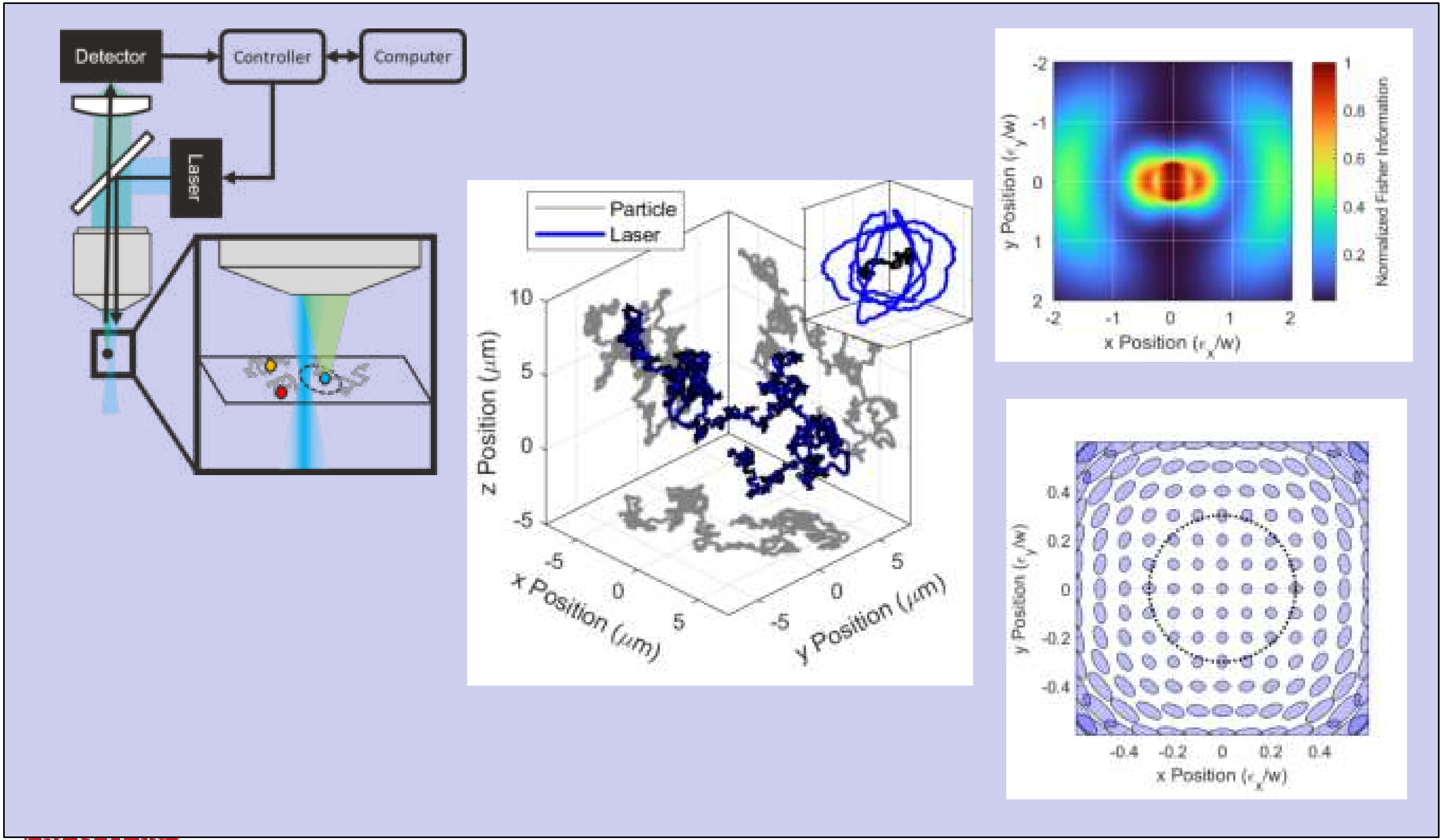
Collaboration with R. Tron

Biophysics


Detector
Controller
Computer
Laser
Particle
Laser
z Position (μm)
x Position (μm)
y Position (μm)
Normalized Fisher Information
x Position (ϵ_x/w)
y Position (ϵ_y/w)

THANK YOU!

UPCOMING EVENTS

Learn more & RSVP: bu.edu/research/events
Topic ideas & feedback: bu.edu/research/topic-ideas

RESEARCH ON TAP

China and the World
February 27, 2023 | 4-6 pm

Safety, Justice, and Health in US Cities
March 15, 2023 | 4-6 pm

RESEARCH HOW-TO

Learn to Use the Dimensions Database
February 15, 2023 | 1-2:30 pm

Guide to Op-Eds: How to Improve your Writing, Editing, and Pitching
February 16, 2023 | 3-4:30 pm