Berkeley Engineering

Educating Leaders. Creating Knowledge. Serving Society.

New Vistas in Robotics at Berkeley

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Director, Blum Center for Developing Economies

Director, C3.ai Digital Transformation Institute

Univ of California Berkeley

An Overview of the Telesurgical Workstation Project

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Key Collaborators: Frank Tendick, Ron Fearing
Department of Bioengineering
University of California, Berkeley and San Francisco
Berkeley, CA 94720

Telesurgical Workstations

- Minimally invasive—small incisions: millirobotic tools: surgeon is remote!

Robotic tools give surgeon dexterity and tactile sensations of force, hardness, etc.

Improved imaging, 3D displays: AR/VR Environments

Shankar Sastry

Laparoscopic Manipulators

Two stage design

- First, for gross positioning of the end effector is a Stewart platform-like parallel manipulator, driven by electric motors, giving 4 degrees of freedom.
- Second, the 3 DOF millirobot has a 2 DOF wrist and gripper, driven by hydraulic actuators. The millirobot's design is optimized to provide enough dexterity to perform suturing and knot-tying tasks.

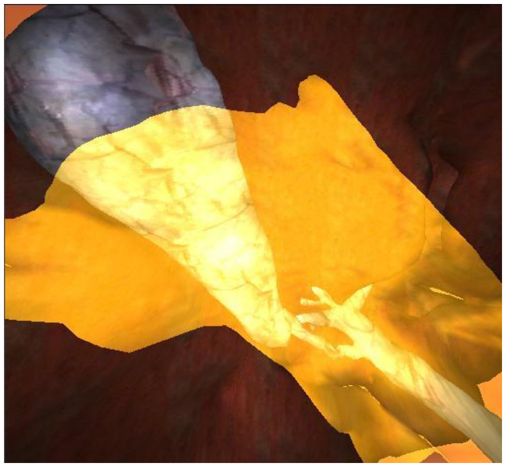
Telesurgical Workstation

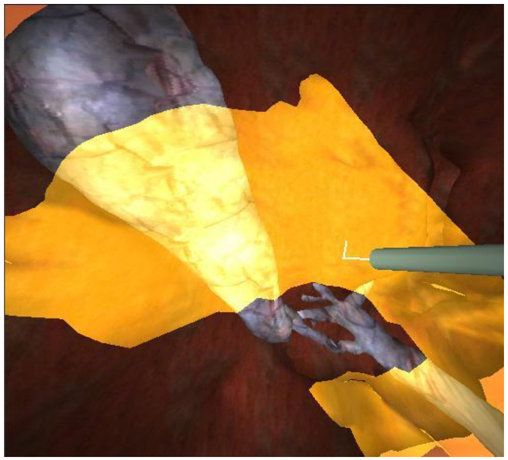
ANIMAL LAB TRIALS 1998

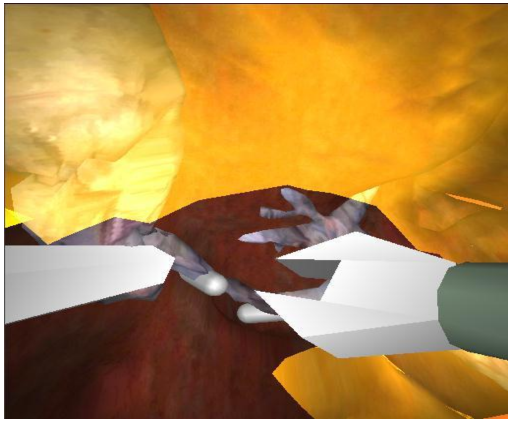
Suturing with Unimanual System, 1998

Laparoscopic Cholecystectomy VR Simulation

Frank Tendick, Michael Downes, M. Cenk Cavusoglu, Shankar Sastry, and Lawrence Way UC San Francisco and UC Berkeley







Future

- Telesurgery
  - Smaller scale manipulators for cardiac and fetal surgery
  - Critical look at the mechanical design of teleoperation systems from control point of view
  - Surgery on the beating heart
- Surgical Simulation
  - Deformable tissue models for dynamic simulation
  - Bridging the gap between finite element, finite difference, and lumped element models, i.e. computer scientists and mechanical engineers

Robotic Surgery Companies Today

- Intuitive Surgical, 2014, Da Vinci
- Stryker, 2013, MAKO (knee and hip surgery)
- Accuray, Cyberknife, partnered with Kuka (radiation therapy)
- Smith & Nephew, NAVIO, knee replacement
- Mazor Robotics, 2012, Mazor X, neurosurgery
- Auris Health, MONARCH robotic bronchoscopy (now J&J)
- ….

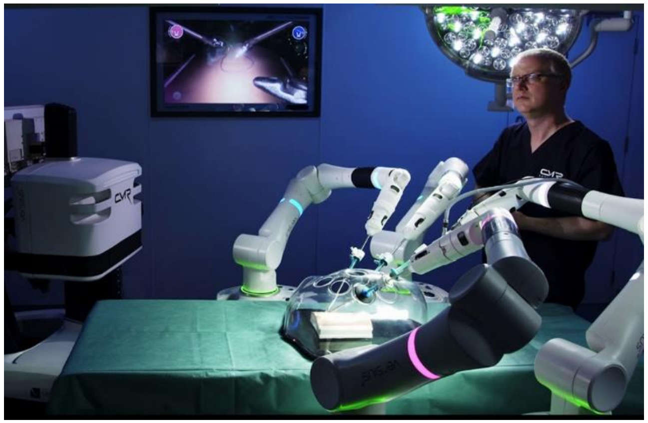
Intuitive Surgical Da Vinci System
https://intuitive.com

- As minimally invasive surgery expands, Academic Medical Centers will continue to play a large role in preparing the surgeons of tomorrow for its latest modalities, including da Vinci robotic-assisted surgery.
- There are currently 350+ da Vinci systems spread across 140 robotics programs in U.S. Academic Institutions, which help 90,000+ patients every year.[1]

Auris Monarch J&J Bronchiboscopy System

- For remote insertion of Bronchioscopes.
- Especial need for Covid
- Can it be made less expensive?

Newer Companies



Clockwise from bottom left

1. **ActivSight by ActivSurgical: soft tissue suturing**
2. **Versius by CMR Medical, laparoscopic procedures**
3. **Dexter by Distal Motion, laparoscopic procedures**

The Berkeley Aerial Robot Project (BEAR)

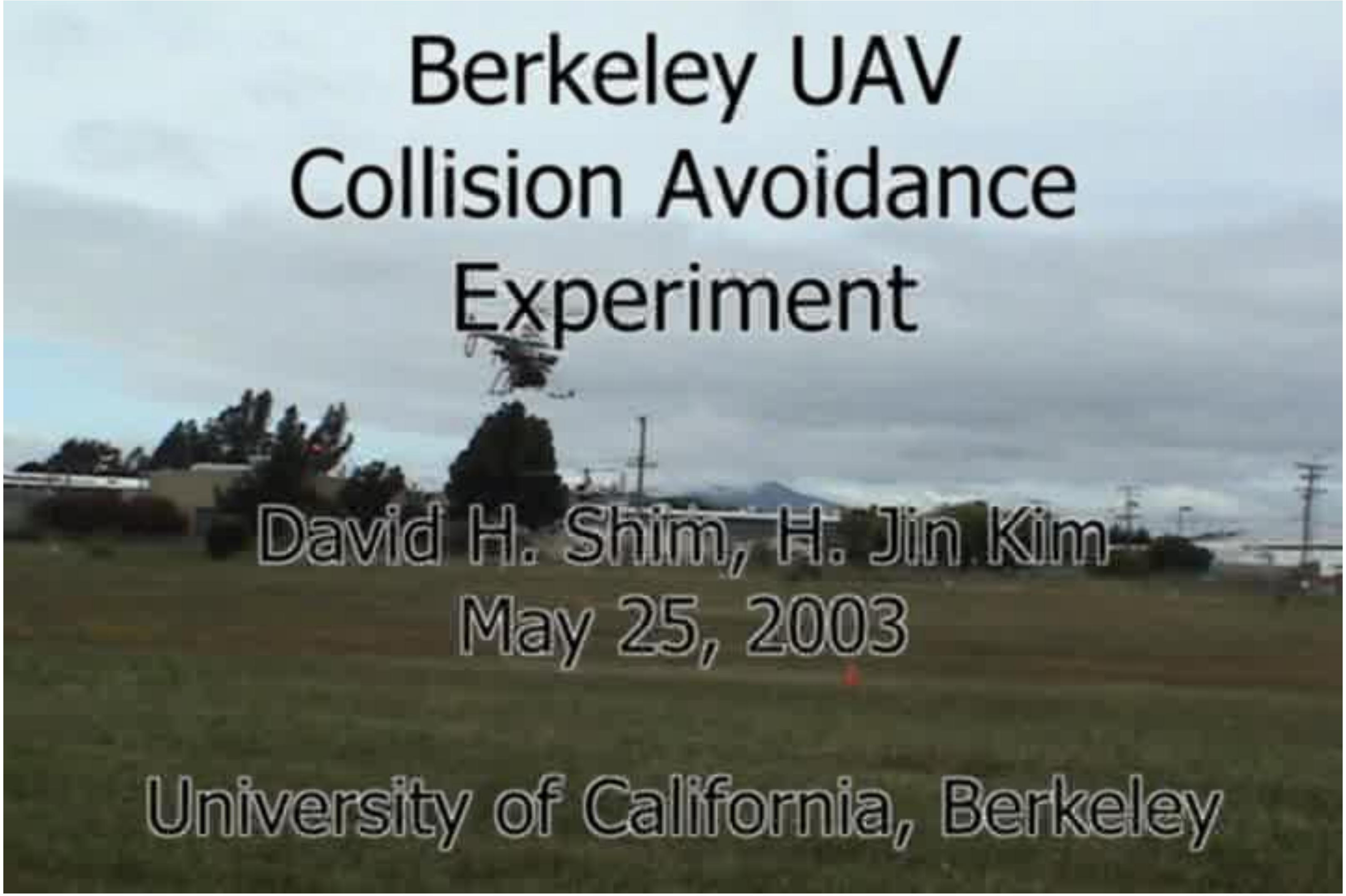
http://robotics.eecs.berkeley.edu/bear

David Shim, Jin Kim, Hoam Chung, Peter Ray, Omid Shakernia, Jonathan Sprinkle, Mike Eklund, Todd Templeton, Travis Pynn, Cory Sharp, Cedric Ma, Rene Vidal, Perry Kavros, Shahid Rashid, Tulio Celano, Bruno Sinopoli, Shawn Shaffert, Andrew Godbehere and Sam Burden with Shankar Sastry

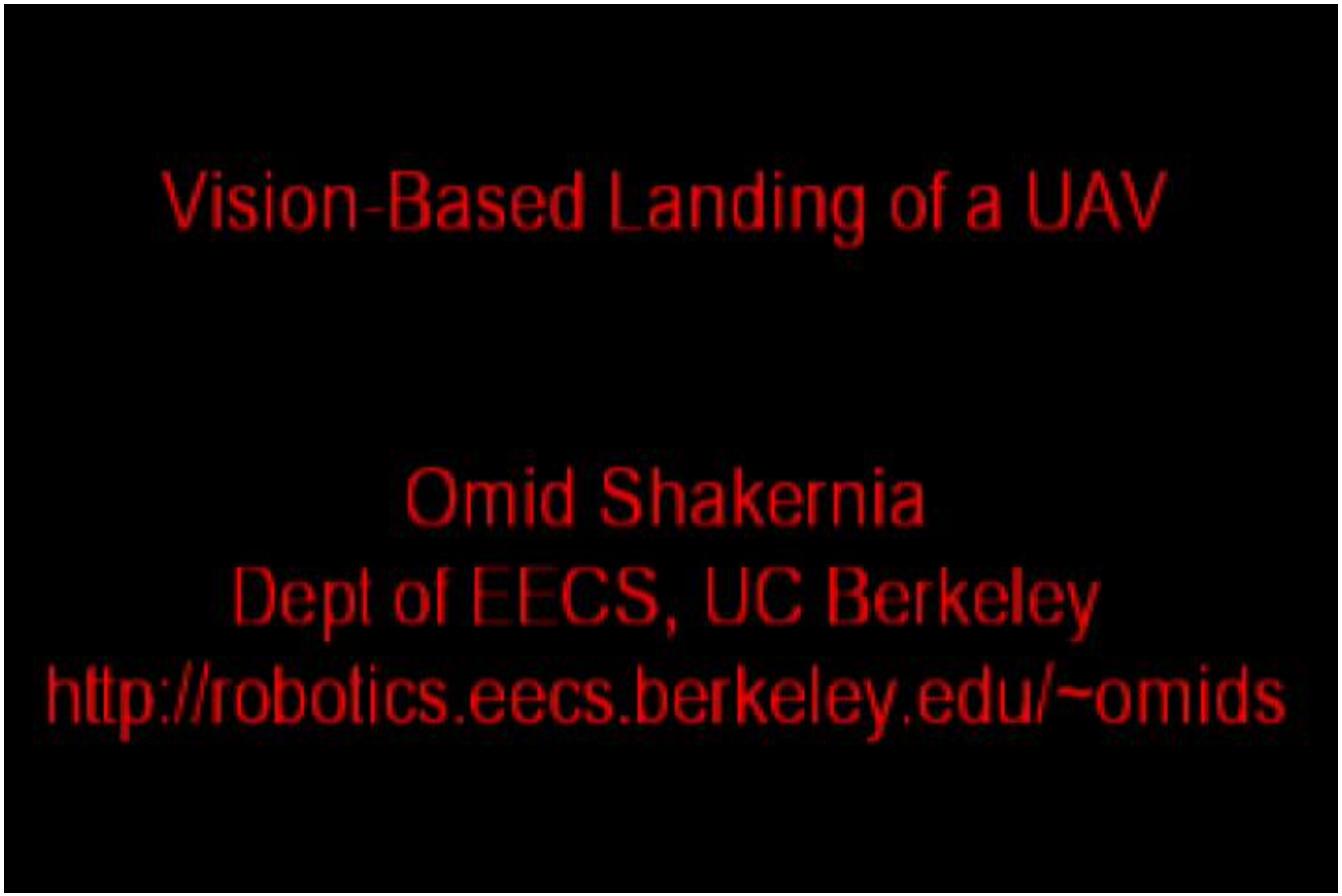
University of California, Berkeley

BEAR Fleet: rotorcraft

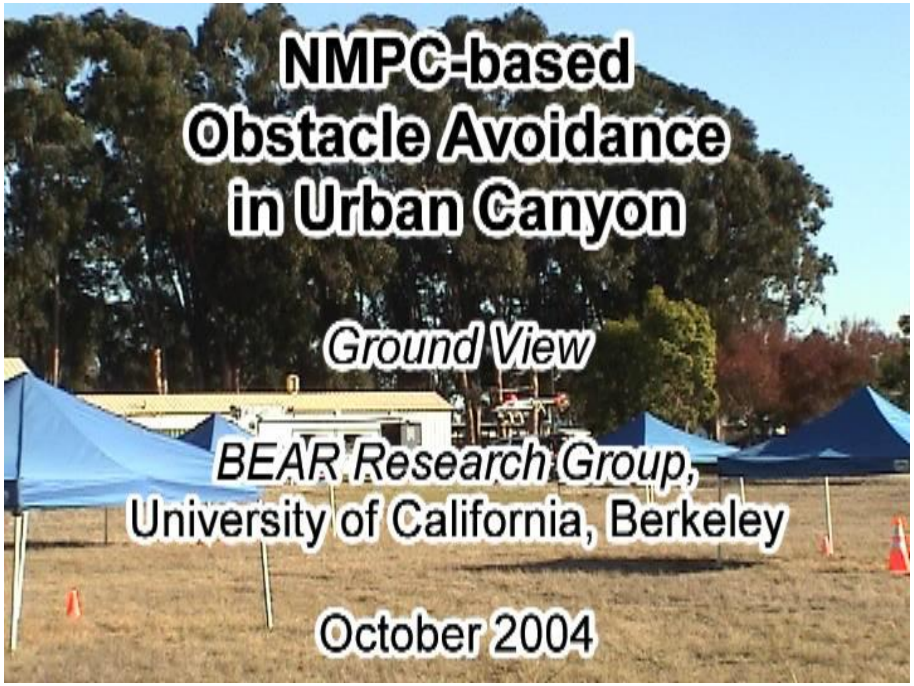
Conflict Detection and Resolution

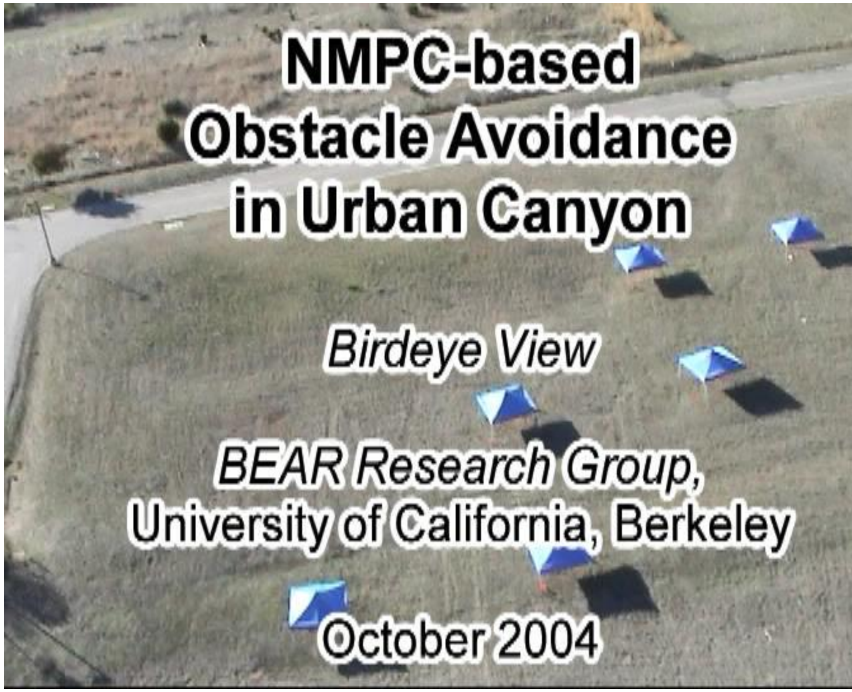


Vision Based Landing



Model Predictive Control Based Path Planningg





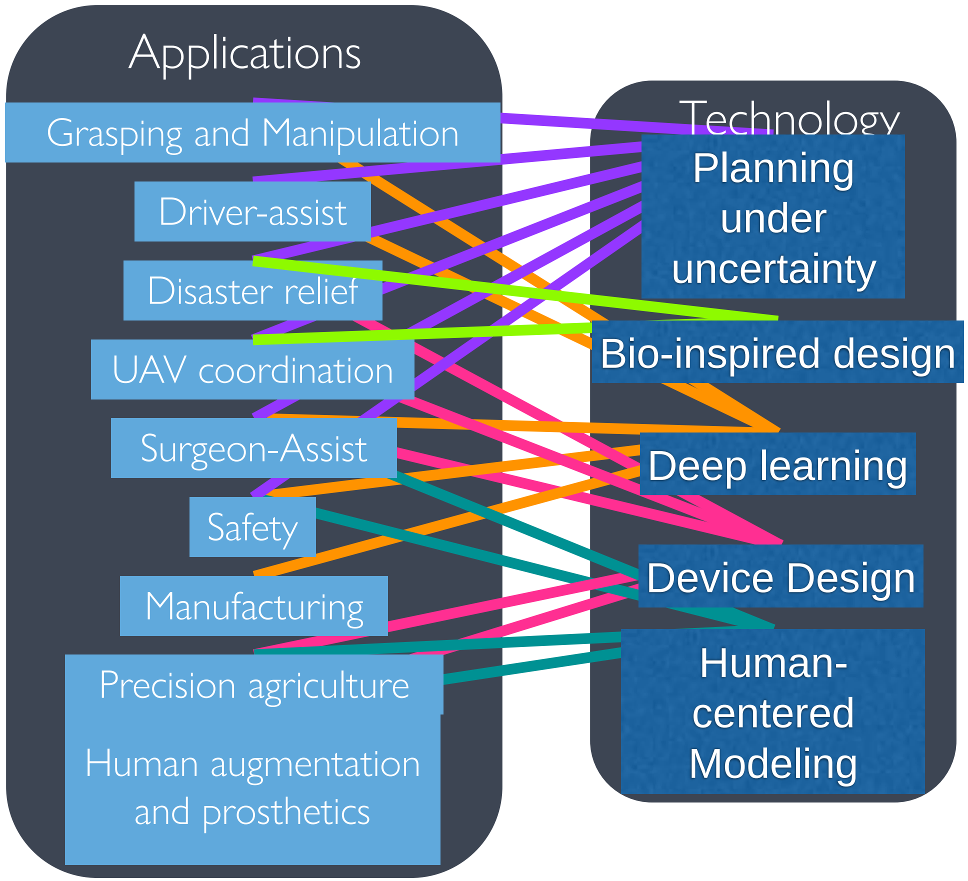
Smart Bird takes flight

Press Coverage of BEAR

BEAR UAV Research Test bed: A Legacy of Innovation and Transition

- Architecture for multi-level rotorcraft UAVs 1996- to date
- Pursuit-evasion games 2000- 2002 (transitioned to AFRL/Darpa/Boeing UCAV program)
- Vision Based landing on pitching decks 2001- to date (transitioned to Socom Boeing-Frontier Systems Maverick/A-160)
- Multi-target tracking 2001- to date (transitioning to 1st MEP, Camp Pendleton)
- Formation flying and formation change 2002-4 (transition begun to Army Socom, 160th SOAR, Sikorsky)
- NMPC Based Acrobatic Flying, conflict resolution 2003 (transitioned to DARPA UCAR, Lockheed, Northrup Grumann)
- Aerial Pursuit Evasion Games 2003 (transitioned to Boeing UCAV program, demo at Edwards AFB, June 2004)
- Automated Landing transitioned to Northrup Grumann (demo at Edwards AFB, June 2004)
- Sensor Webs (low bandwidth air dropped sensor webs demonstrated at China Lake, Feb 04): now Smart Bird personal UAVs
- Personal back pack sized UAVs (Smart Bird), April 2004-ongoing
- Perch and Move Electric UAV Vehicles, August 2004
- Map Building and Collision Avoidance, November 2004
- Vision Based Landing transitioned to Boeing Frontier, demo first autonomous landing Dec 2005

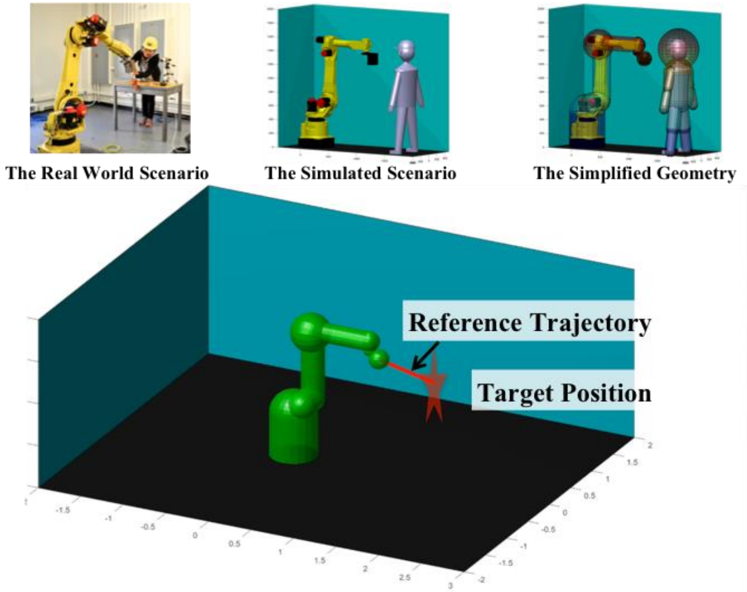
CITRIS “People and Robots” Initiative



Cloud Robotics

1. Big Data: Images, maps, models
2. Cloud Comp.: Statistical learning
3. Open-Source: Sharing code, data, designs
4. Robot Learning: Robots sharing code, data
5. Crowdsourcing: Input from remote humans

Manufacturing



Masayoshi Tomizuka

Ken Goldberg

Paul Wright

Data-Driven Grasping and Manipulation

DexNet: A cloud-based network of 3D objects for robust grasp planning

Algorithms for efficient grasp quality evaluation

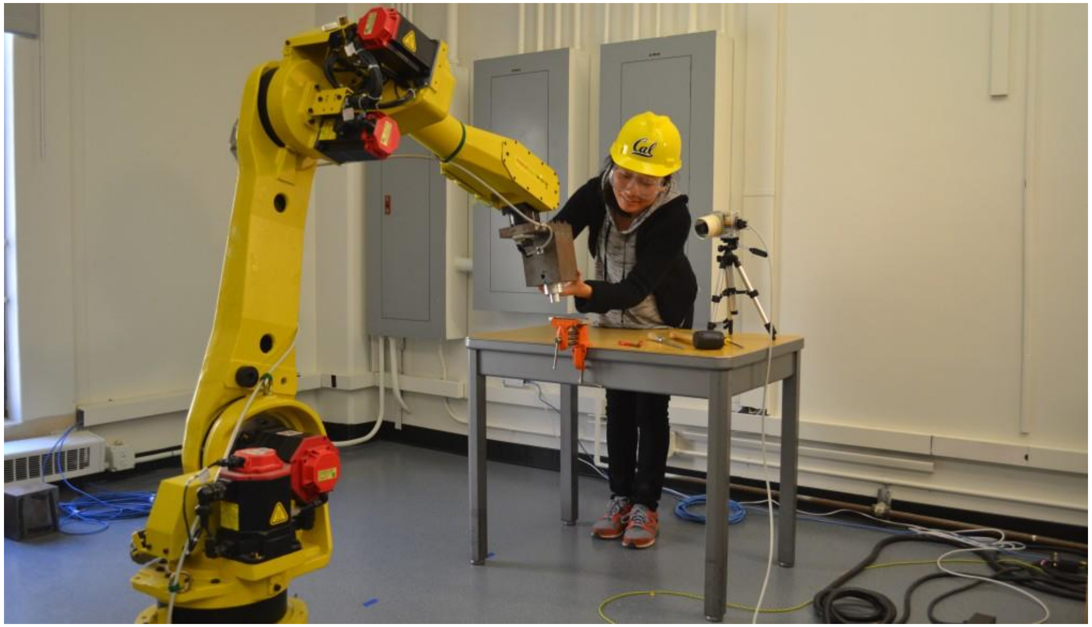
Energy-bounded caging

Topological motion planning for grasping and manipulation

Ken Goldberg

Pieter Abbeel

Safety in Human-Robot Interaction



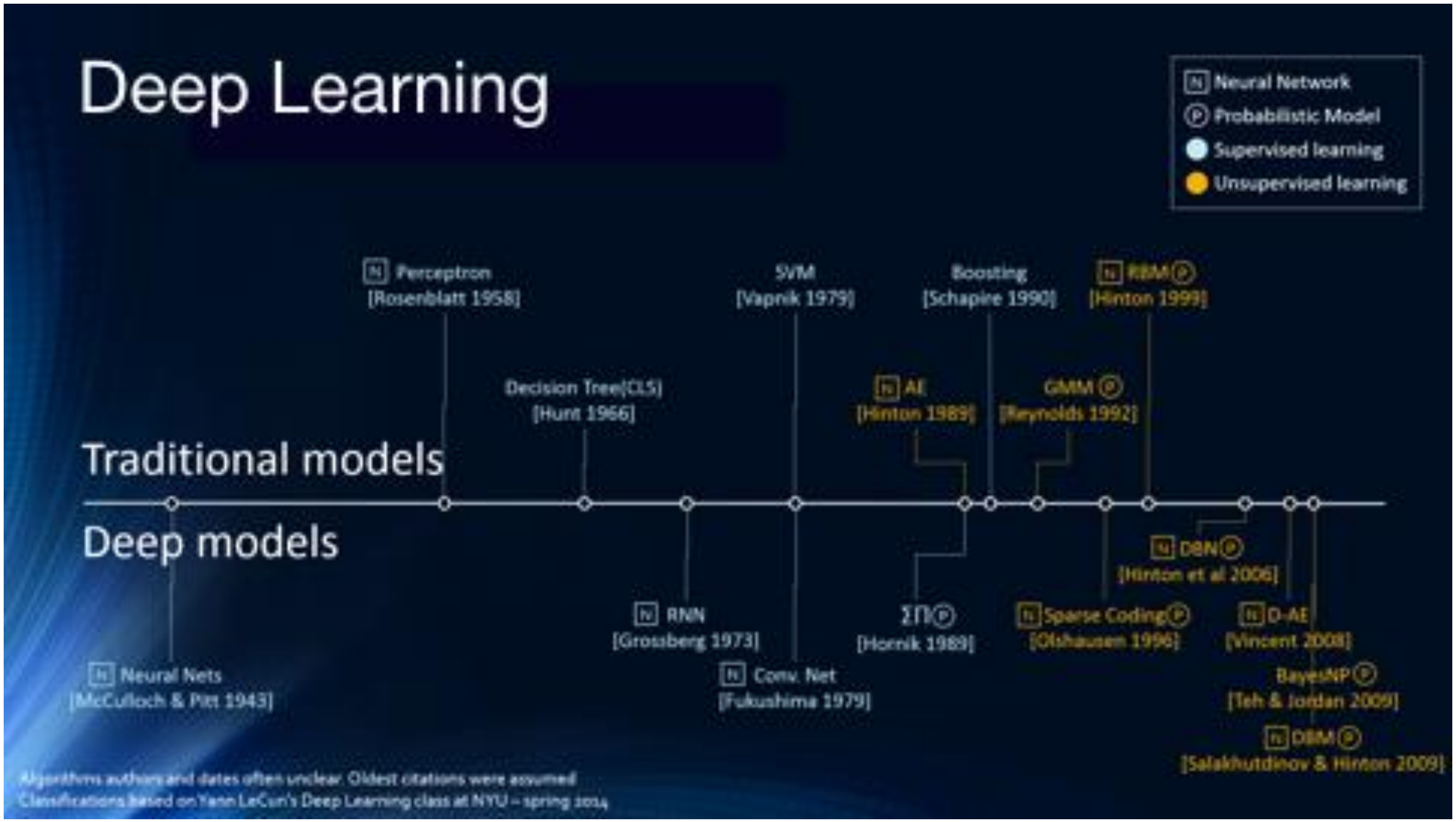
Safety-constrained motion planning for efficiency in factory human-robot interaction

Learning and prediction for safety in HRI

Provably safe human-centric autonomy

Claire Tomlin

Masayoshi Tomizuka


Deep Learning
Neural Network
Probabilistic Model
Supervised learning
Unsupervised learning
Traditional models
Deep models
Neural Nets
[McCulloch & Pitt 1943]
Perceptron
[Rosenblatt 1958]
Decision Tree(CLS)
[Hunt 1966]
RNN
[Grossberg 1973]
SVM
[Vapnik 1979]
Conv. Net
[Fukushima 1979]
AE
[Hinton 1989]
ΣΠ
[Hornik 1989]
Boosting
[Schapire 1990]
GMM
[Reynolds 1992]
Sparse Coding
[Olshausen 1996]
RBM
[Hinton 1999]
DBN
[Hinton et al 2006]
D-AE
[Vincent 2008]
BayesNP
[Teh & Jordan 2009]
DBM
[Salakhutdinov & Hinton 2009]
Algorithms authors and dates often unclear. Oldest citations were assumed
Classifications based on Yann LeCun's Deep Learning class at NYU – spring 2014

Deep Learning for Robotics

Learning deep visuomotor policies: enable robots to autonomously acquire new skills by learning from human demonstrations

Simultaneous transfer across domains

Deep learning for locomotion

Unsupervised Trajectory Segmentation of Multi-Modal Surgical Demonstrations with Deep Learning

Trevor Darrell

Pieter Abbeel

Ken Goldberg

Reducing Supervisor Burden for Robot Learning

Learning from demonstrations

Learning deep visuomotor policies: enable robots to autonomously acquire new skills by learning from human demonstrations

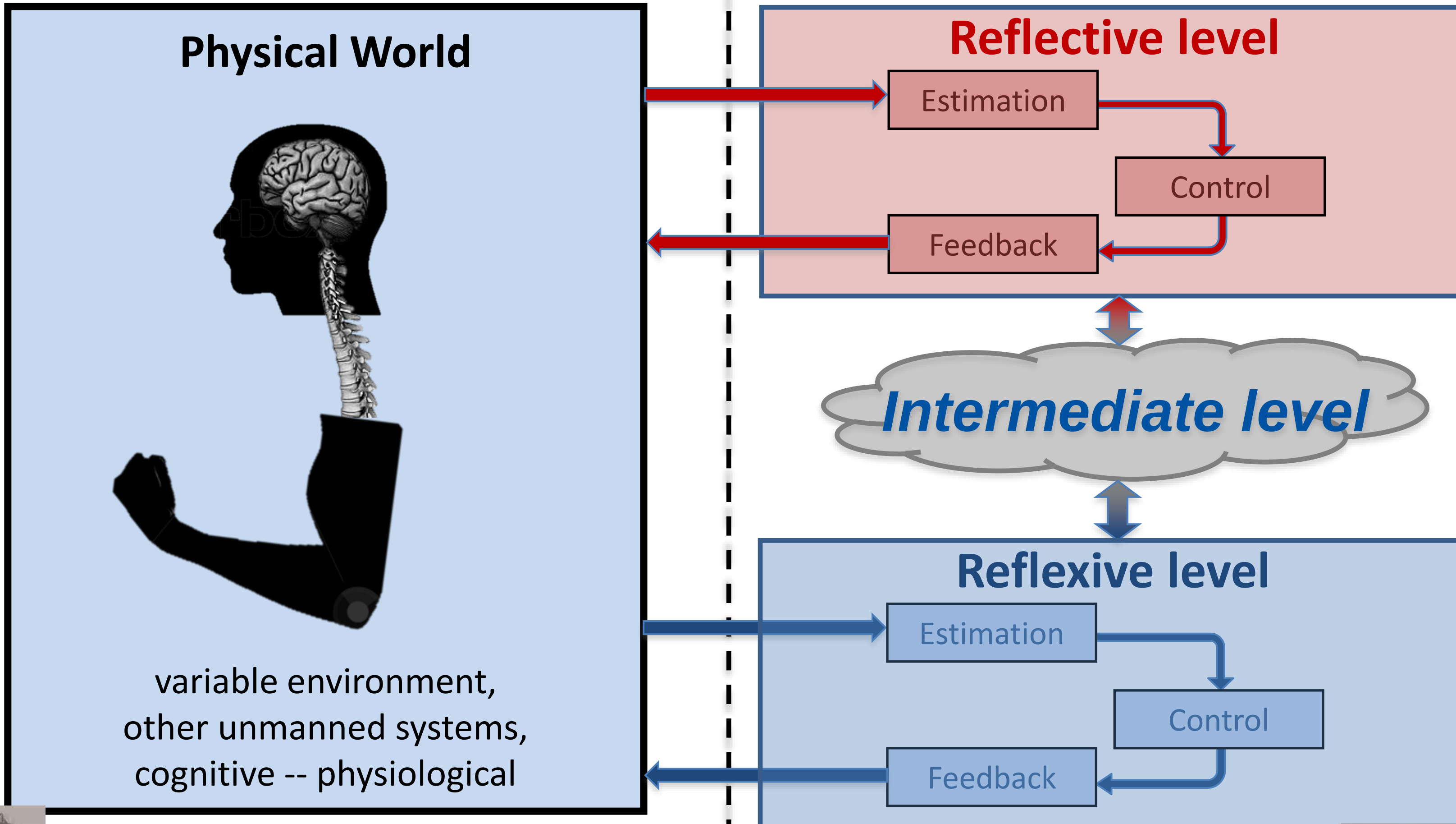
Cooperative inverse reinforcement learning: understanding value alignment between humans and machines

Indirect learning from humans: context and motion from archived video

Ken Goldberg

Pieter Abbeel

Embedding Humans in Automation



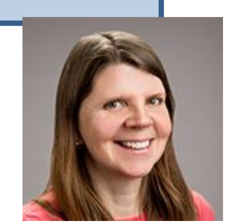
Human

Shankar Sastry

Anca Dragan

Automation

Claire Tomlin

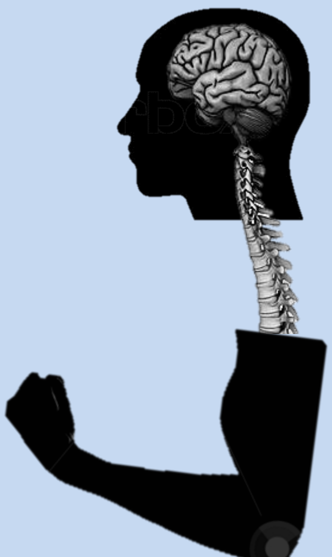


High Confidence Robotic Assistants

Physical World

safety-critical dynamical system, control by human is stochastic

$$x_{k+1} = f_k(q_k, x_k, u_k)$$



Estimation

human variability, cognitive state

$$\widehat{q}_k$$

Control

assumption mining enables safety verification

$$\exists\psi : \psi \rightarrow \varphi$$

Feedback

alter system dynamics, task specification

$$\psi \rightarrow \varphi$$

Shankar Sastry

Human

Robot

Claire Tomlin

Interaction with Humans

Google's Driverless Cars Run Into Problem: Cars With Drivers

By MATT RICHTEL and CONOR DOUGHERTY SEPT. 1, 2015

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MOUNTAIN VIEW, Calif. — Google, a leader in efforts to create driverless cars, has run into an odd safety conundrum: Its cars don't make enough mistakes.

Last m
approa
suppos
pedestr
to appl
not so r
behind

Google's fleet of autonomous test cars is programmed to follow the letter of the law. But it can be tough to get around if you are a stickler for the rules. One Google car, in a test in 2009, couldn't get through a four-way stop because its sensors kept waiting for other (human) drivers

The Google self-driving car, with Eric Schmidt, left, the company's executive chairman, and Transportation Secretary Anthony Foxx. Justin Sullivan/Getty Images

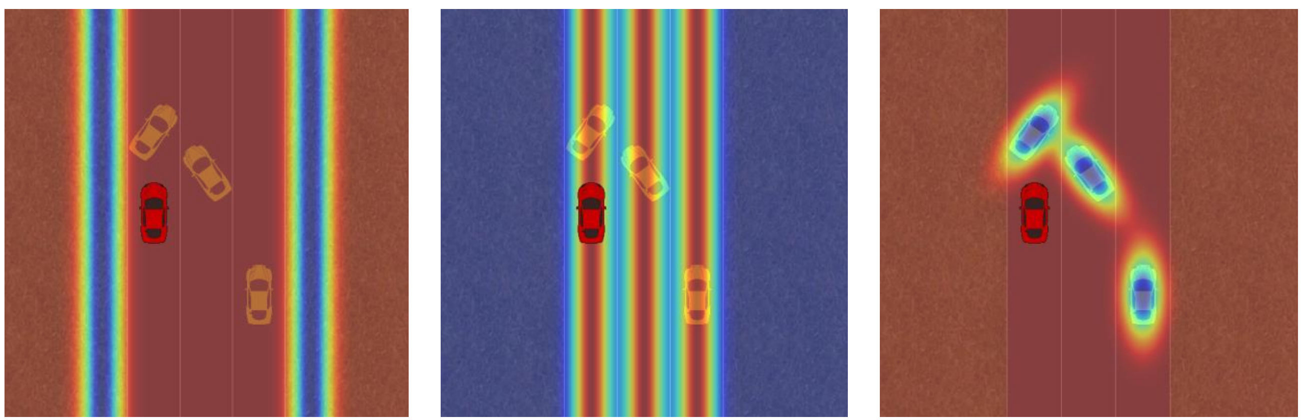
"One of the biggest challenges facing automated cars is blending them into a world in which humans don't behave by the book."

Learning Driver Models

Learn Human's reward function based on Inverse Reinforcement Learning:

$$P(\boldsymbol{u}_H | x_0, w) = \frac{\exp(R_H(x_0, \boldsymbol{u}_R, \boldsymbol{u}_H))}{\int \exp\big(R_H(x_0, \boldsymbol{u}_R, \tilde{\boldsymbol{u}}_H)\big)\, d\, \tilde{\boldsymbol{u}}_H}$$

$$r_H\big(x^t, u_R^t, u_H^t\big) = w^\top \phi(x^t, u_R^t, u_H^t)$$

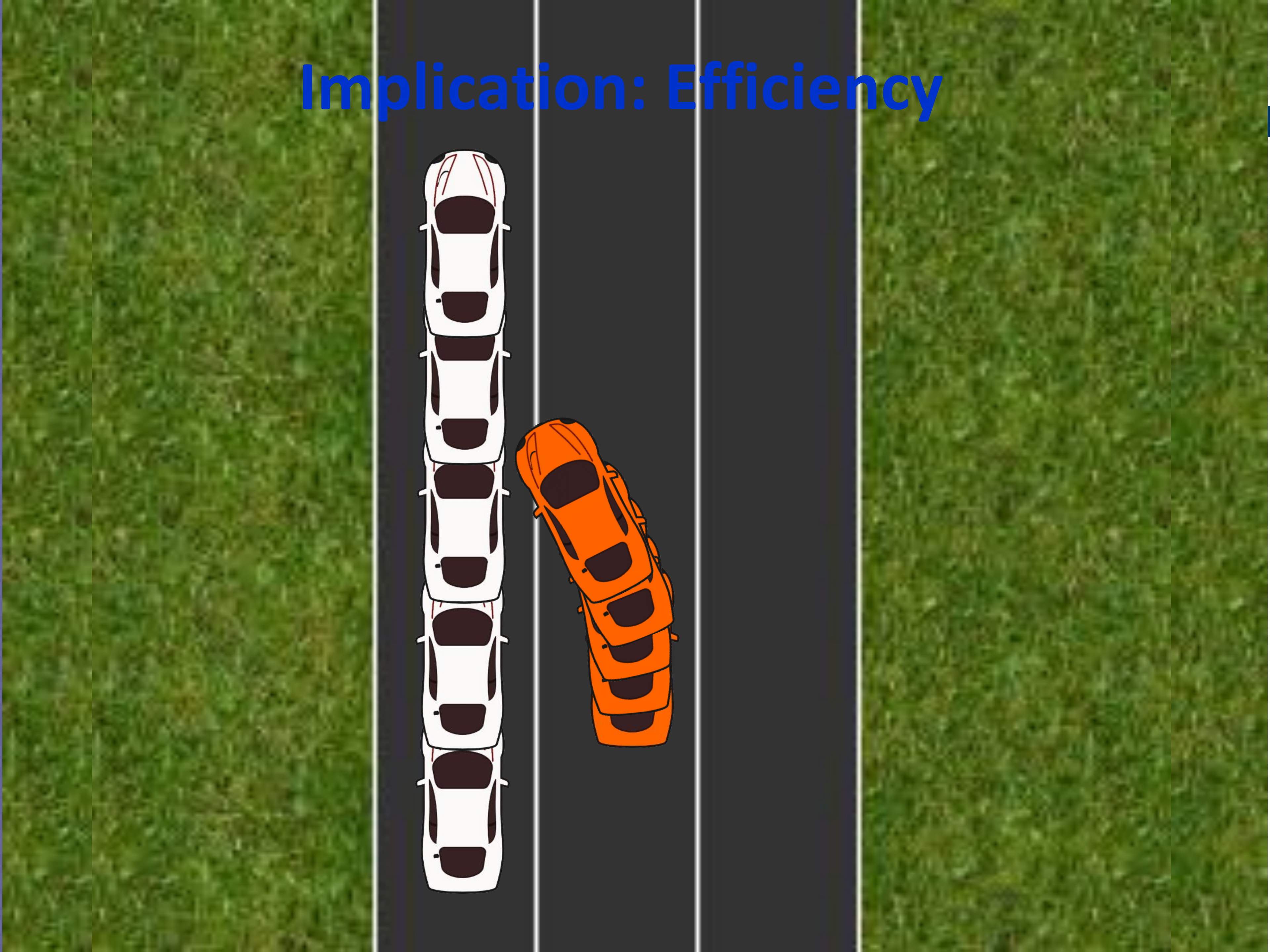


(a) Features for the boundaries of the road

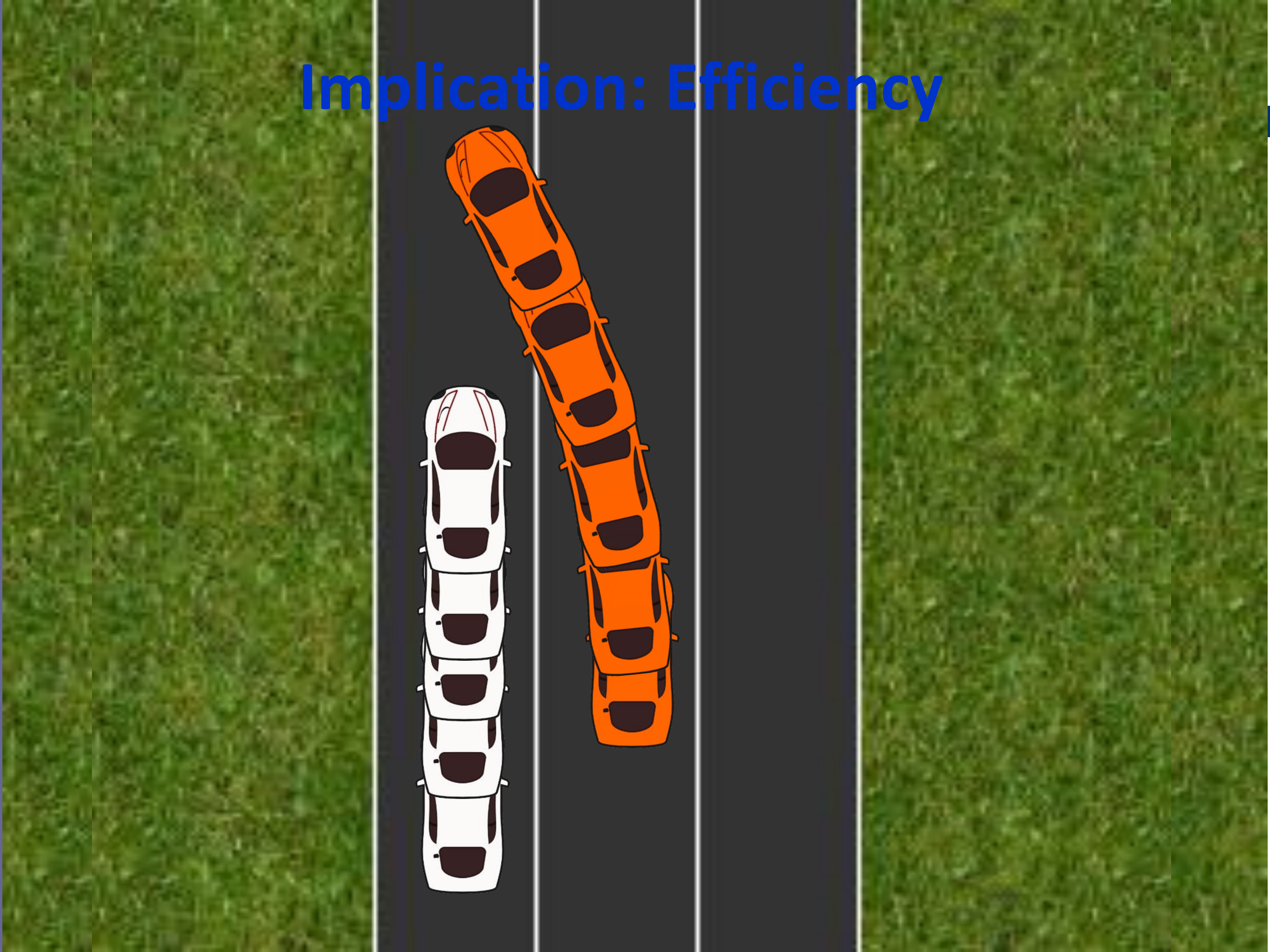
(b) Feature for staying inside the lanes.

(c) Features for avoiding other vehicles.

Implication: Efficiency



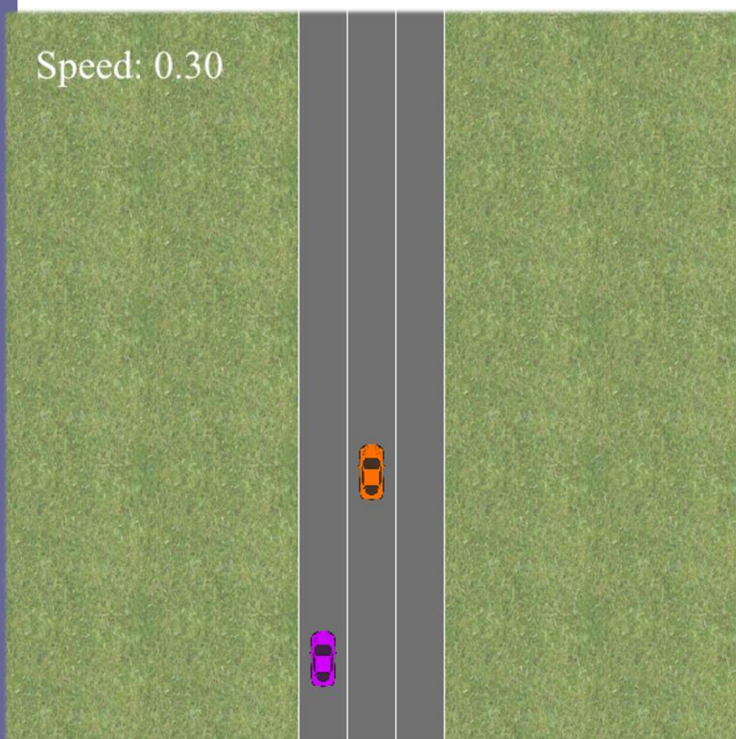
Implication: Efficiency

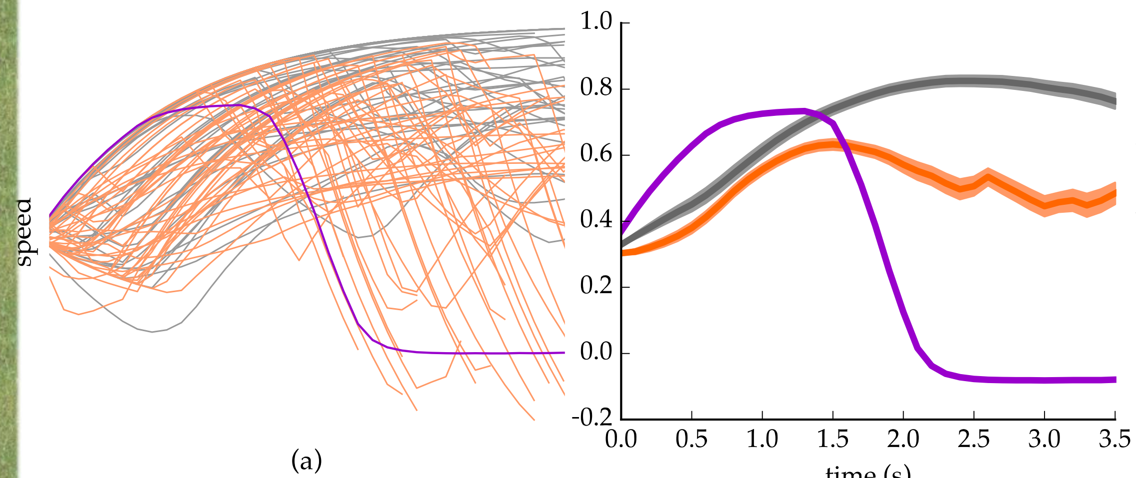


Make Human Slow Down

Autonomous vehicle optimizes for efficiency, and leverages affects on the human.

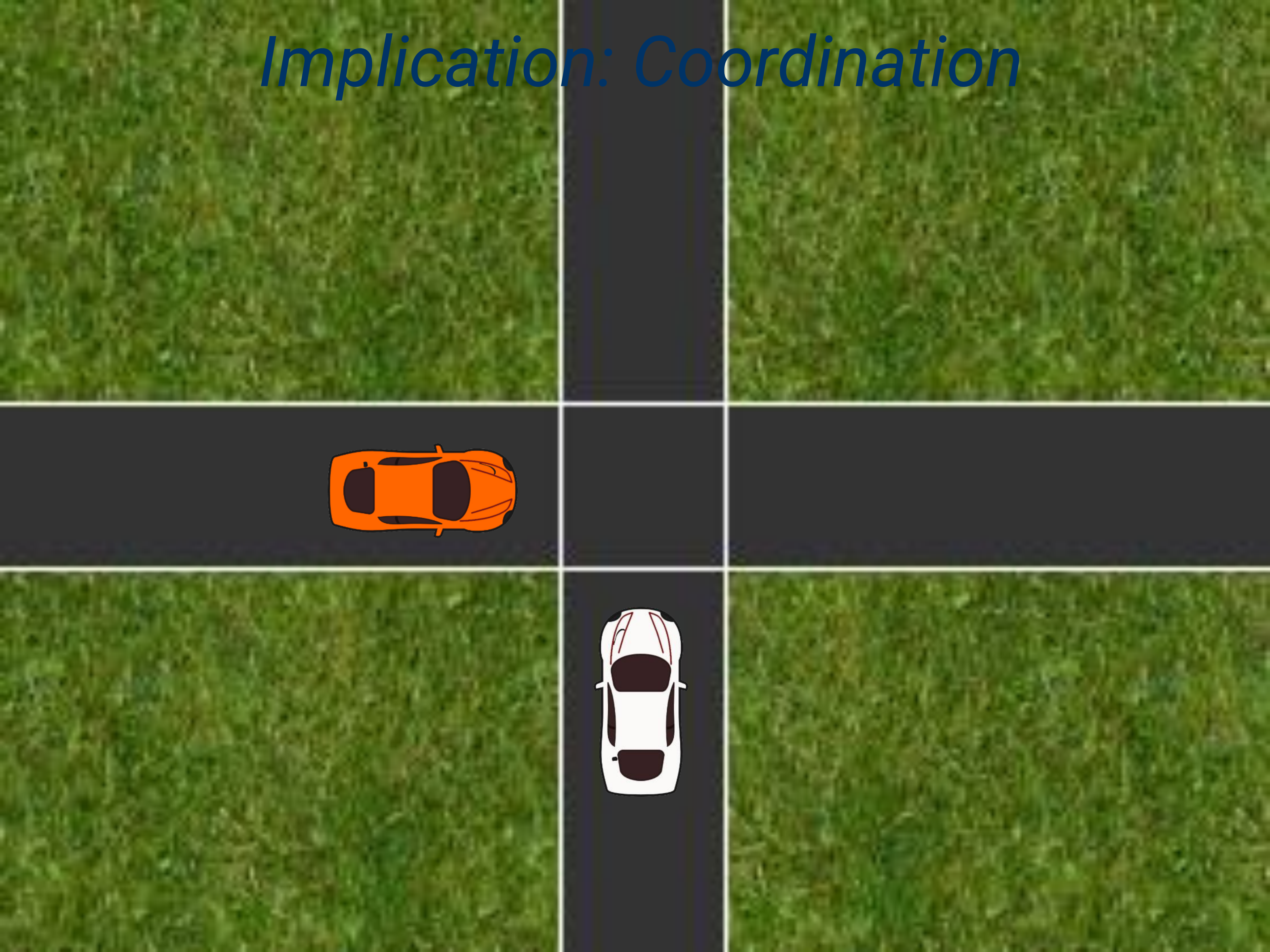
Affect Humanb
Avoid Human
Trained Human Mo





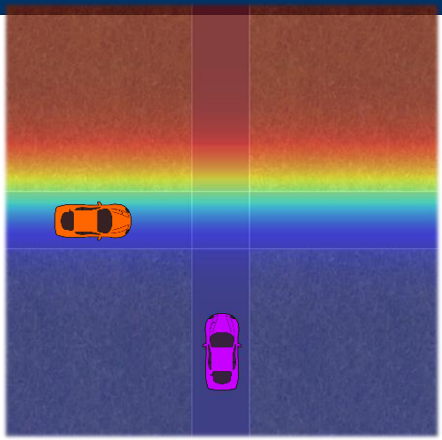
(a)
(b)

Implication: Coordination

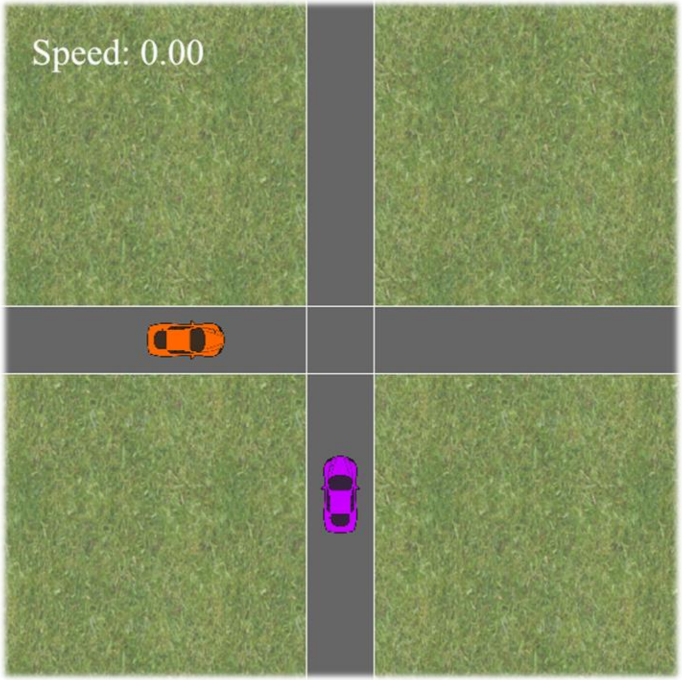


Implication: Coordination

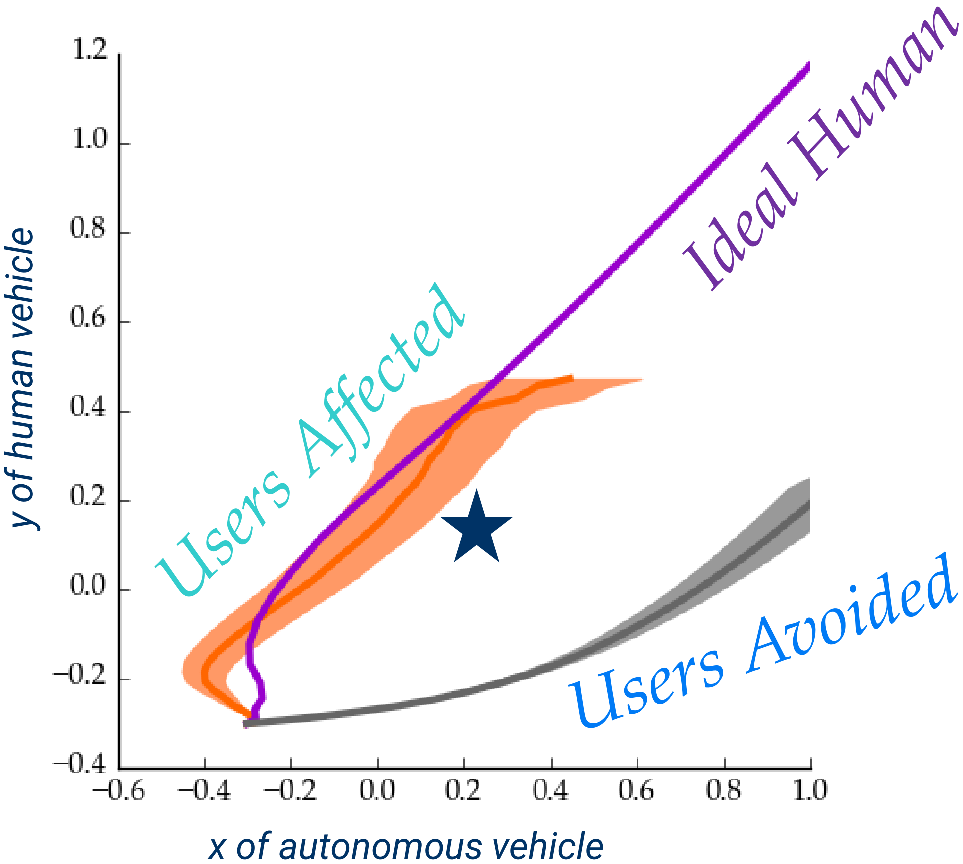
Make Human Cross First



Reward for making the human cross first.



Autonomous vehicle backs up to communicate with the human, and make her cross first.



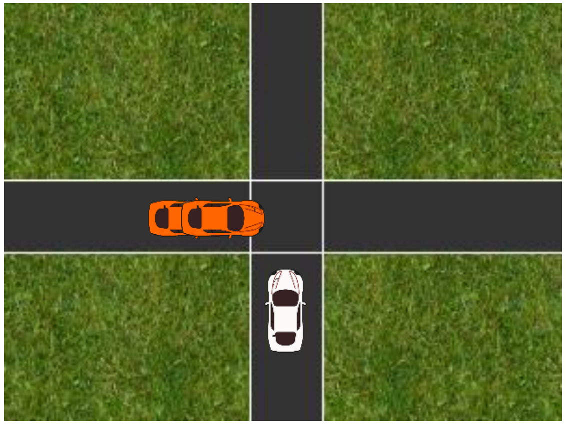
Active Information Gathering

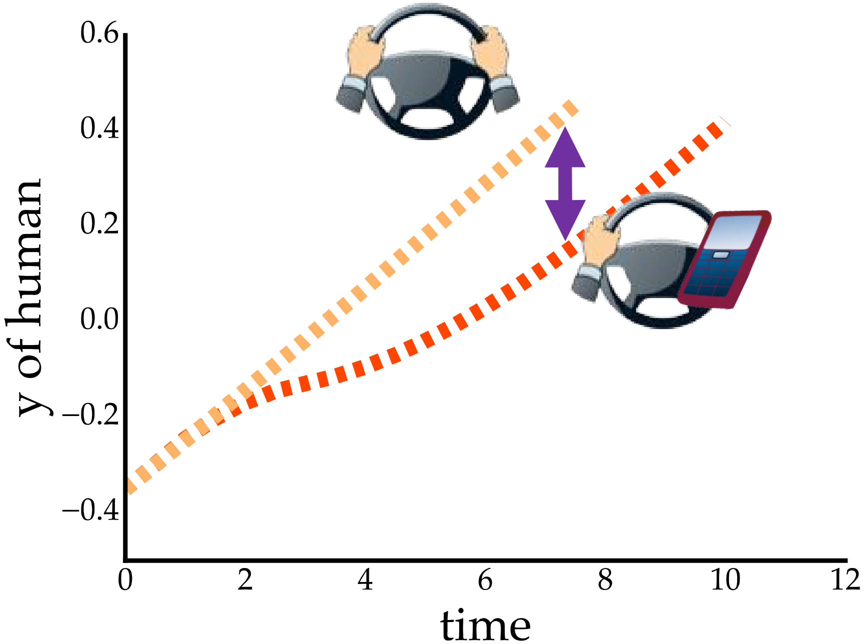
Active information gathering *over human's internal state.*

Human's internal state:

φ : *Aggressive vs Timid*

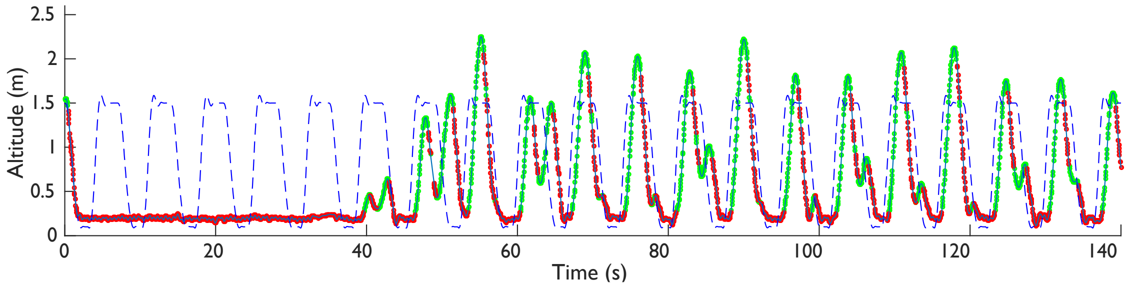
Attentive vs Distracted





D. Sadigh, S. S. Sastry, S. Seshia, A. Dragan. Information Gathering Actions over Human Internal State. IROS 2016.

Safe Learning



The quadrotor first drops :

After about 1 minute,
it can roughly track the trajectory

Soon, it starts experimenting

…but the safe controller steps in

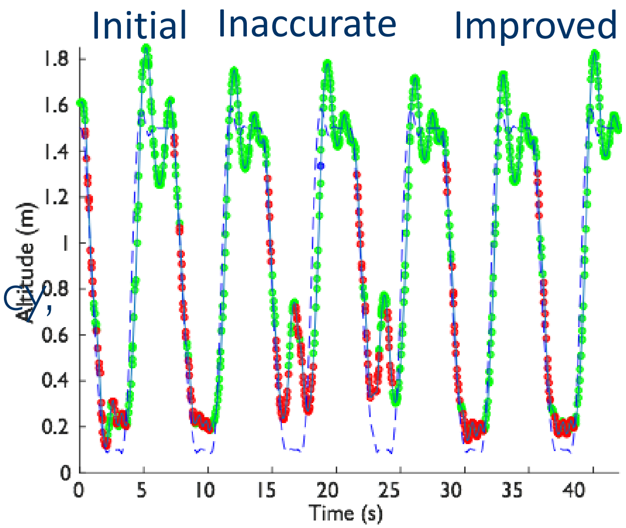
Claire Tomlin

Safe Learning: UAVs in Flight

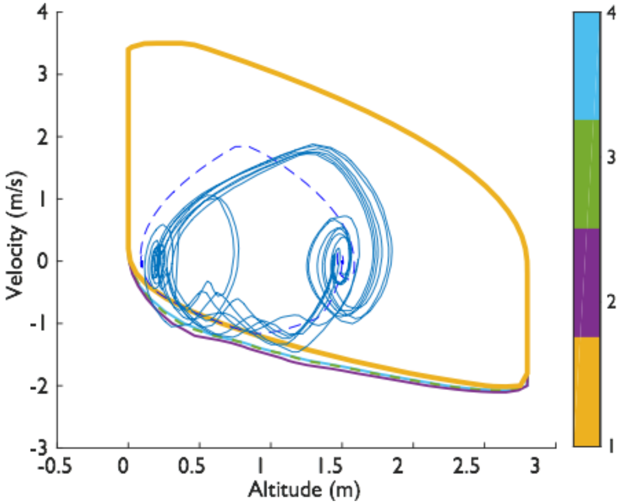
First computed model is locally inaccurate

System detects inconsistency, slightly contracts safe set

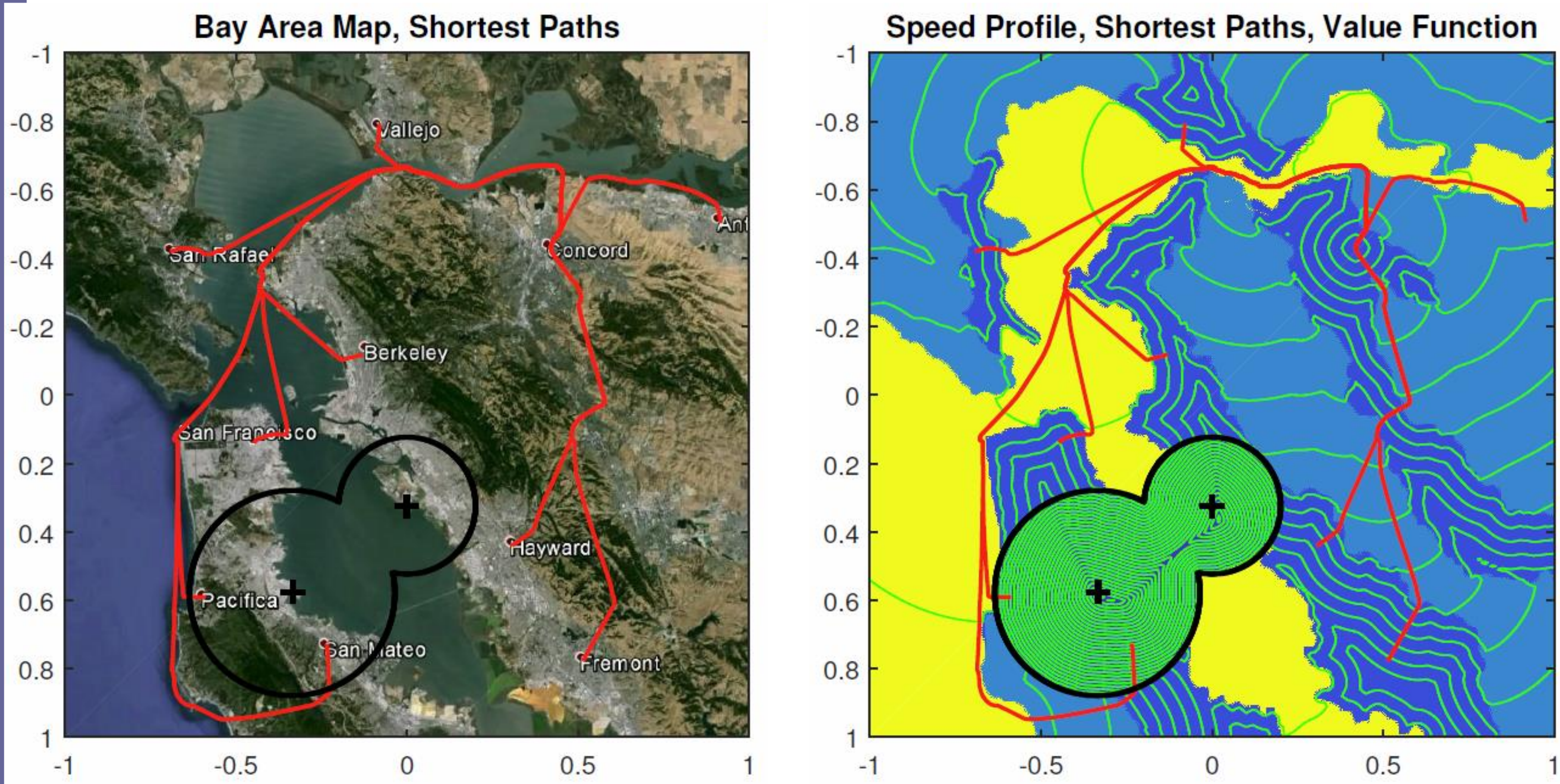
Tracking resumes after a better model is computed



Claire Tomlin



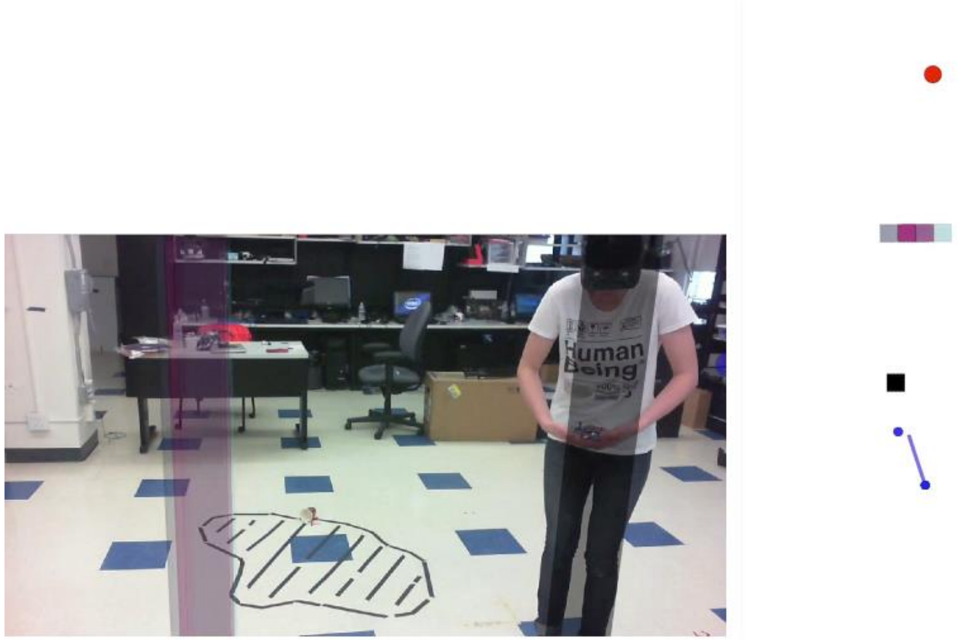
Unmanned Air Traffic Mgmt: Platooning UAVs



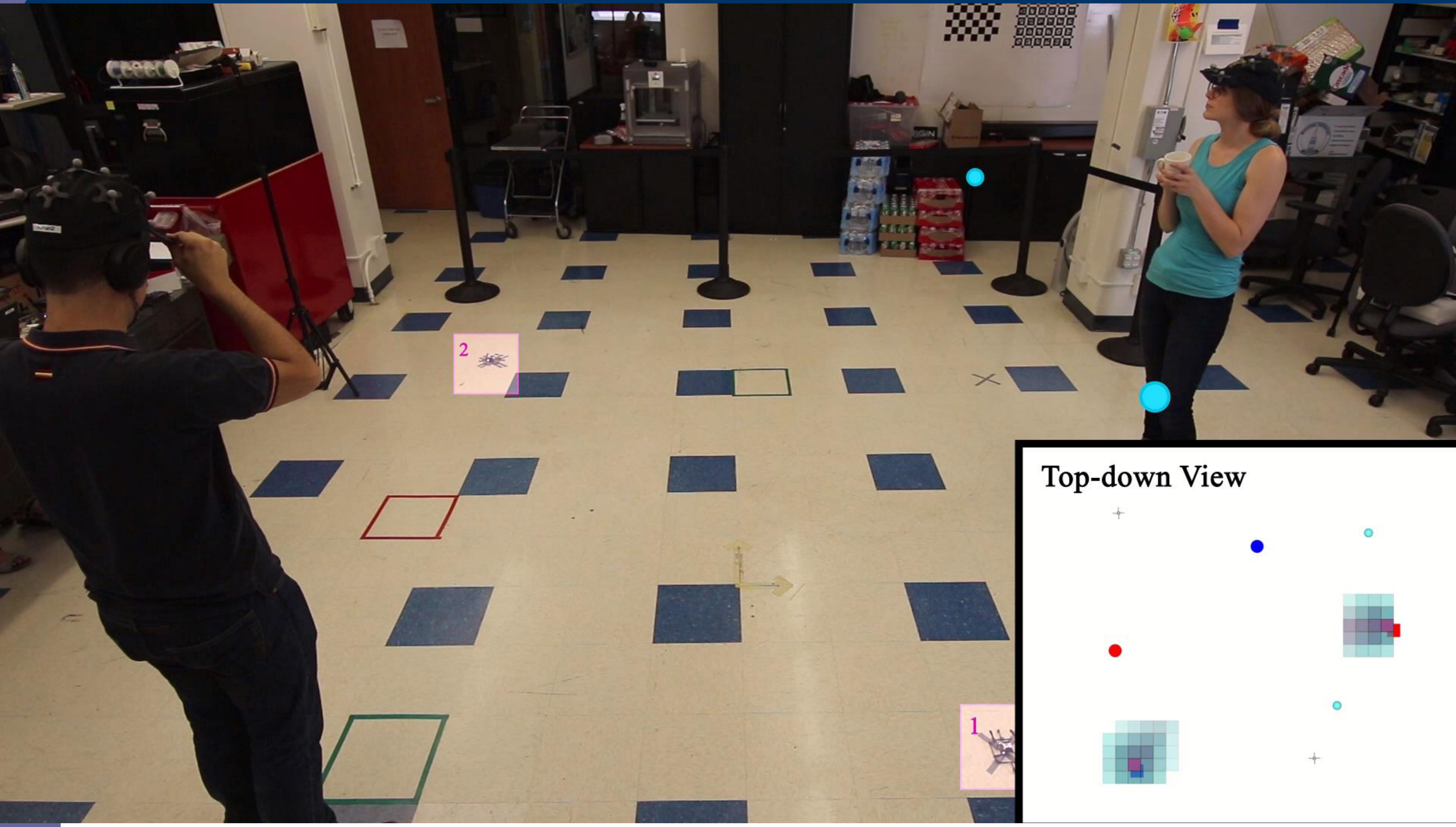
Claire Tomlin

Maneuvering around people

[Bajcsy, Fisac, Fridovich-Keil, Herbert et al., RSS 2018]

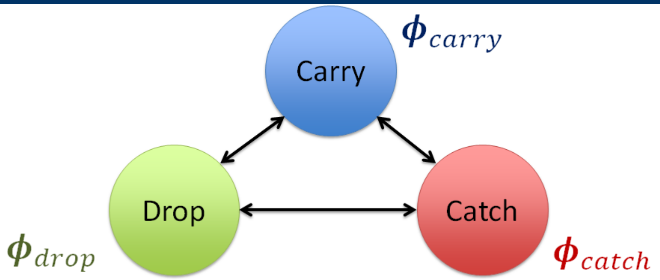


Extending to multiple humans and robots



[Bajcsy, Herbert, Fridovich-Keil, Fisac e

Optimal Assistive Device Design



By modelling the individual and the tasks they need to perform, it is possible to generate the design parameters for assistive devices

Actuator selection, and mechanism design can be determined via optimization methods

These devices are lighter, cheaper and more energy efficient than conventionally designed devices

Ruzena Bajcsy

Prosthetics: Sophie’s Super Hand

Alice Agogino

Robotic Human Augmentation

Low cost and accessible exoskeleton systems for individuals with mobility disorders.

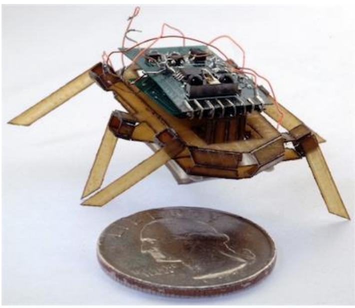
Exoskeletons for strength and endurance augmentation for emergency personnel

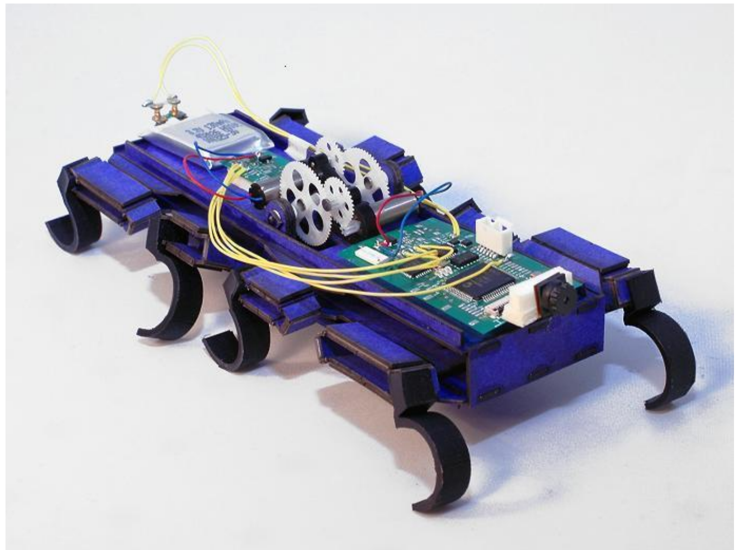
Assistive arms for people with motor impairments

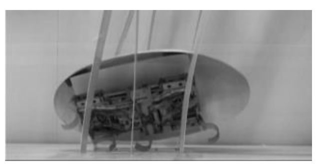
Human power extenders for repetitive lifting in warehouse workers

Homayoon Kazerooni

Bioinspired Milli-Robots







Bio-inspired design

Locomotion and mobility inspired by biology

DIY millirobot rapid prototyping

Micro mechanical flying insects for disaster response

Ron Fearing

Bob Full

Predictive Models of Human Behavior

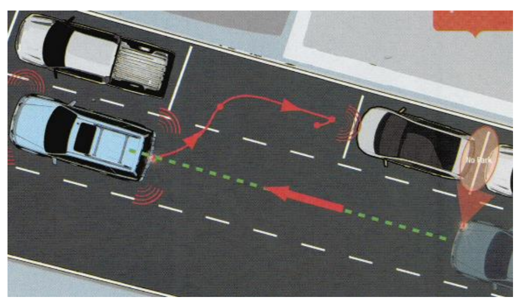
Desk Simulator:
Motion capture/ stereo camera

Force Dynamics Vehicle/Flight Simulator
•High speed multi-axis motion
•Motion capture/ stereo camera

Jaguar
AFS, Ice test

Hyundai
Fully autonomous capability

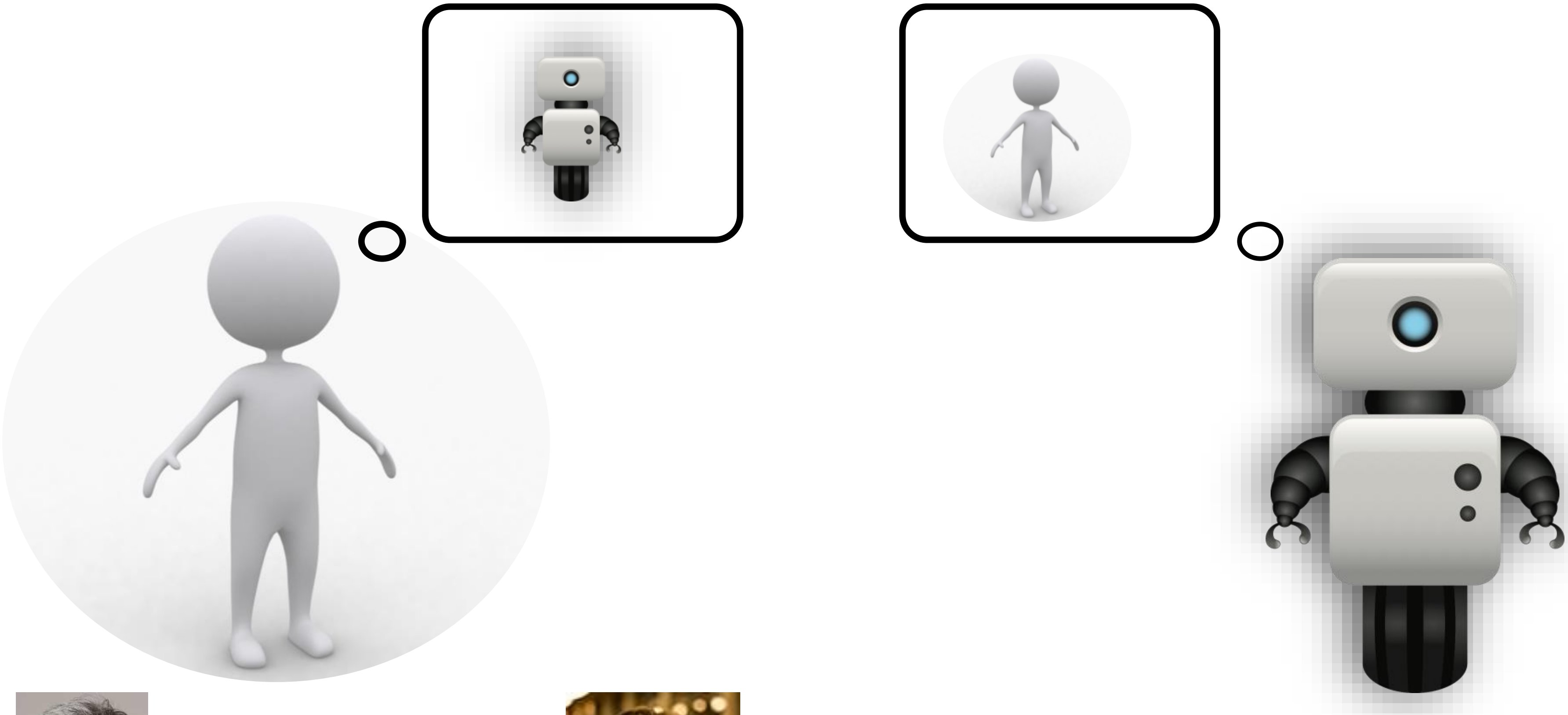
- *Vehicle Dynamics*
- *No Scene Complexity*



- *Non-holonomic Constraints*
- *Static Obstacle Avoidance*

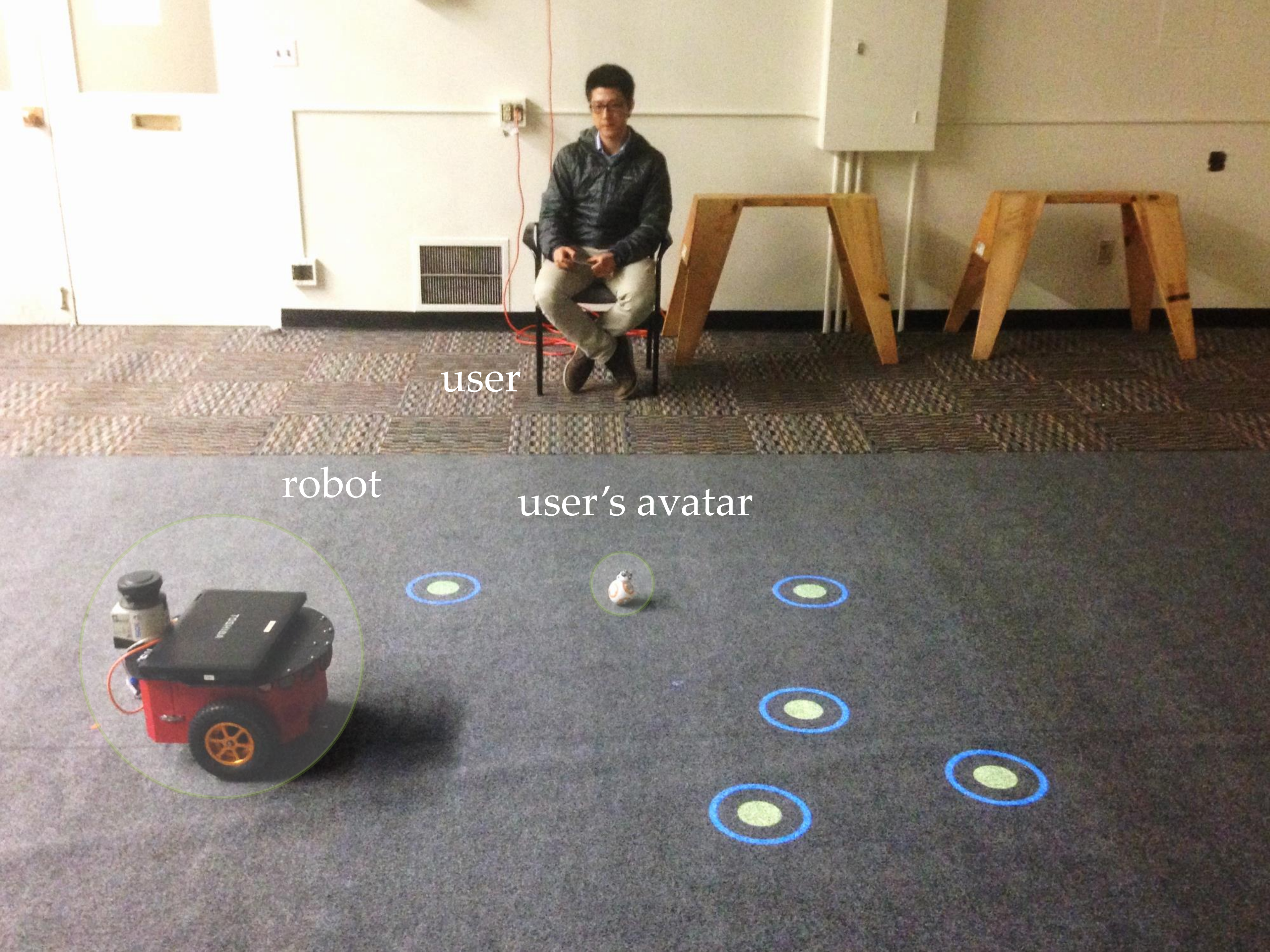
- *Some Scene Complexity*
- *Decision Making + Speed*

Humans and Robots Cooperating

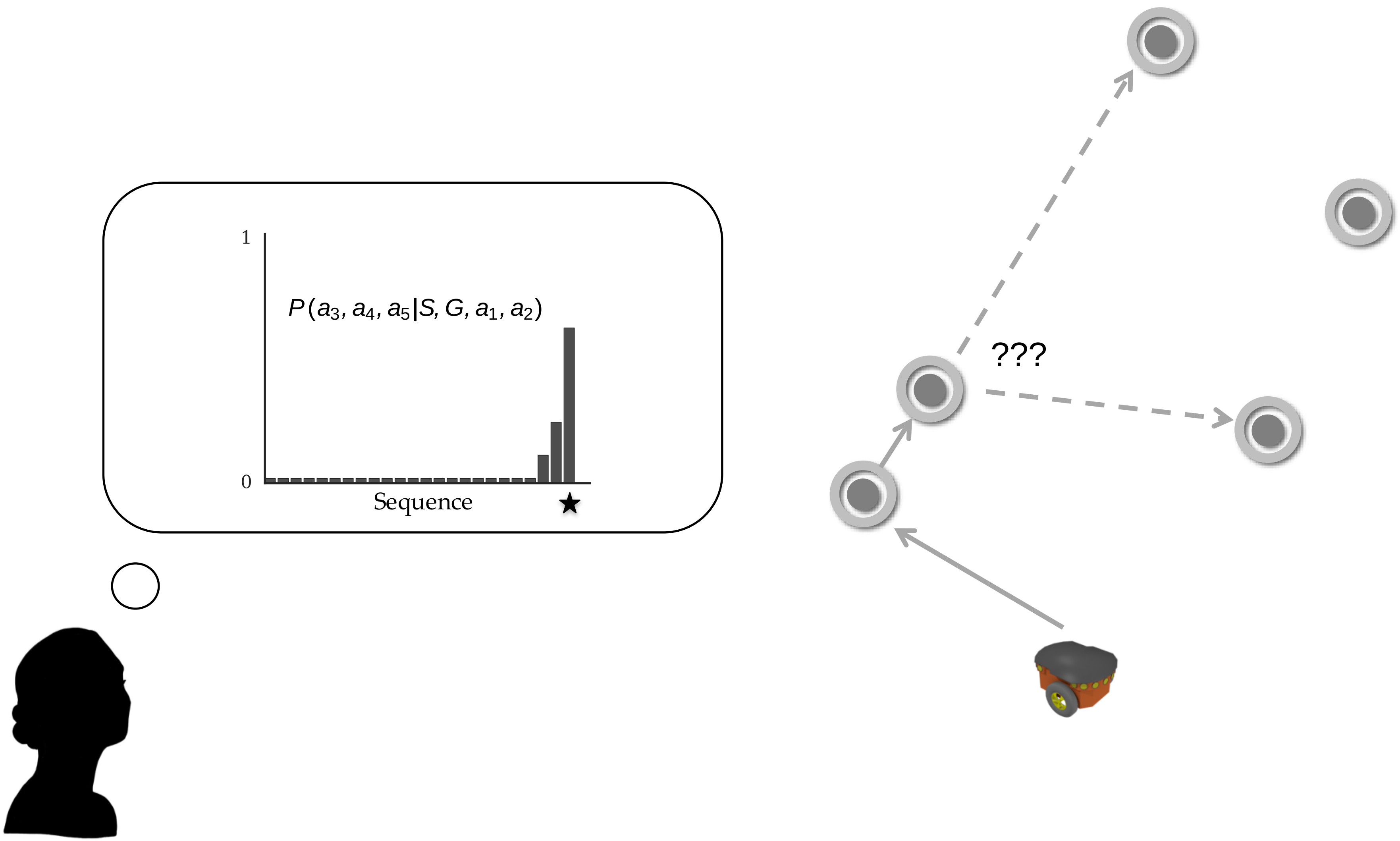


Shankar Sastry

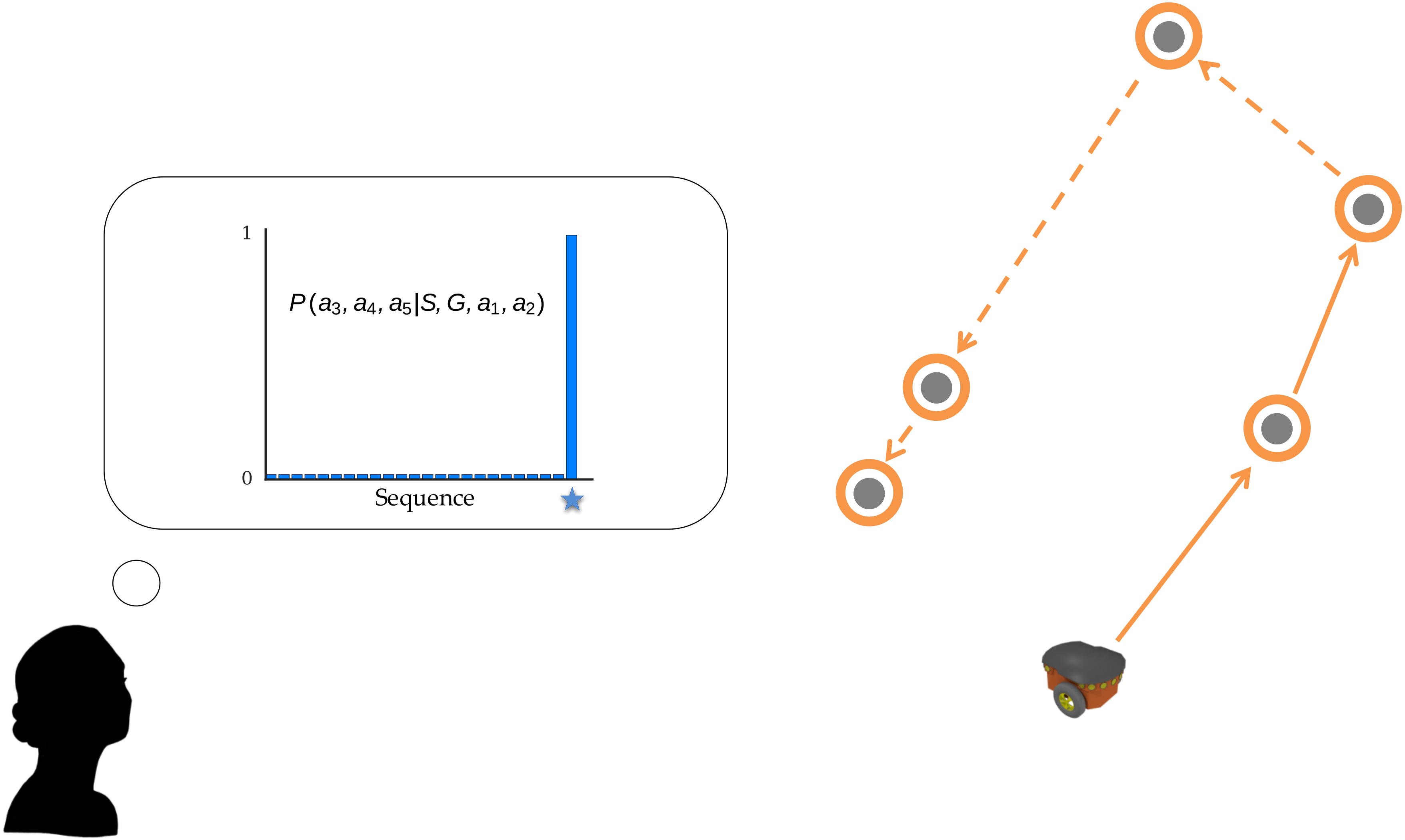
Anca Dragan


user
robot
user's avatar

Efficient can be ambiguous



t-Predictable planning



Tractable *t*-Predictable algorithm

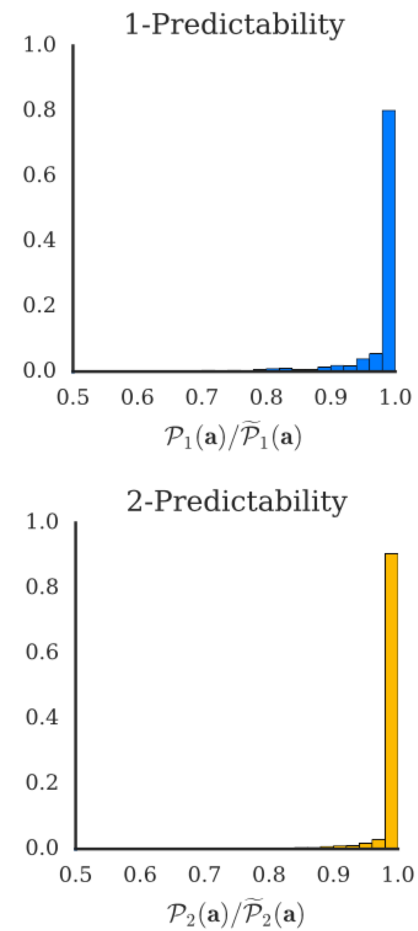
Challenge: evaluating *t*-predictability of a plan requires comparing it to all others sharing the same first *t* steps.

Insight: compare each plan only the best alternative.

Results: speed-up from factorial to exponential time

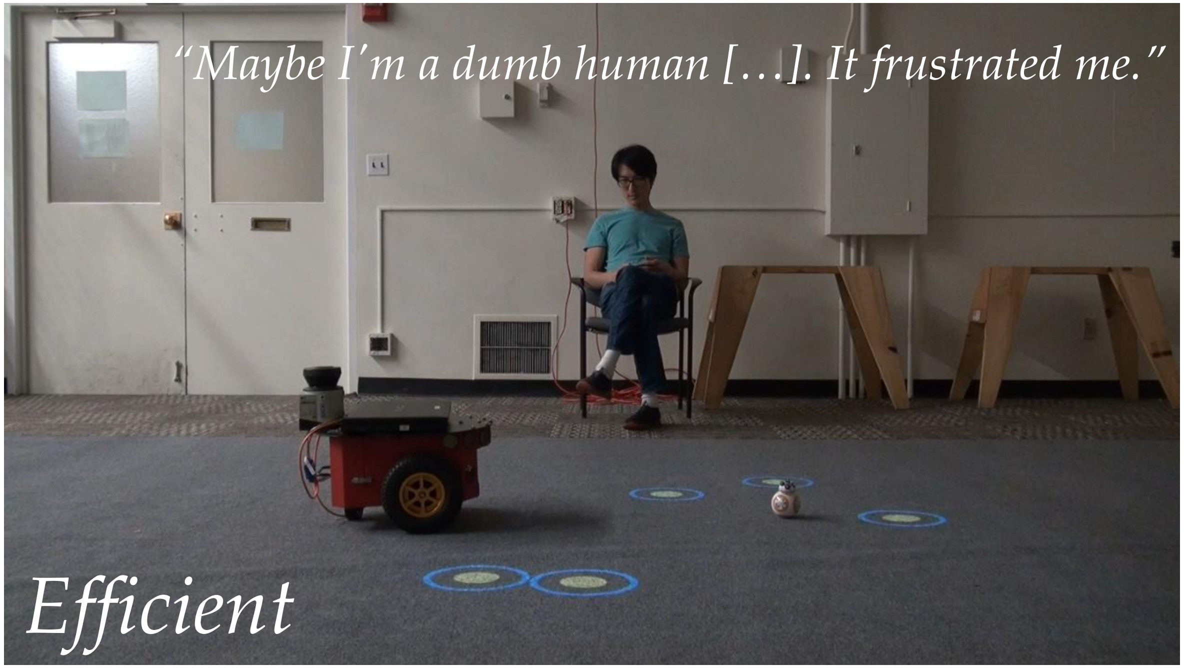
- returns the *exact* solution 90% of the time
- 1% average loss in *t*-predictability *when suboptimal*

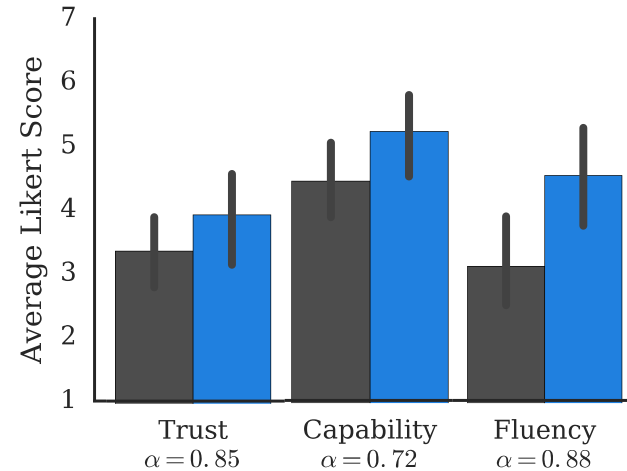
Ratio between exact and approximate t-predictability



J. Fisac*, C. Liu*, J. Hamrick*,
K. Hedrick, S. Sastry, T. Griffiths, A. Dragan

"Generating plans that predict themselves", WAFR 2016

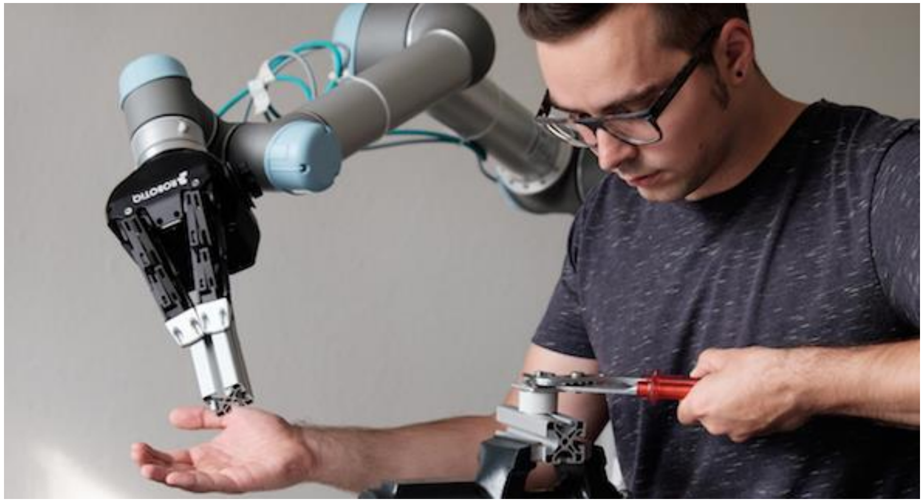


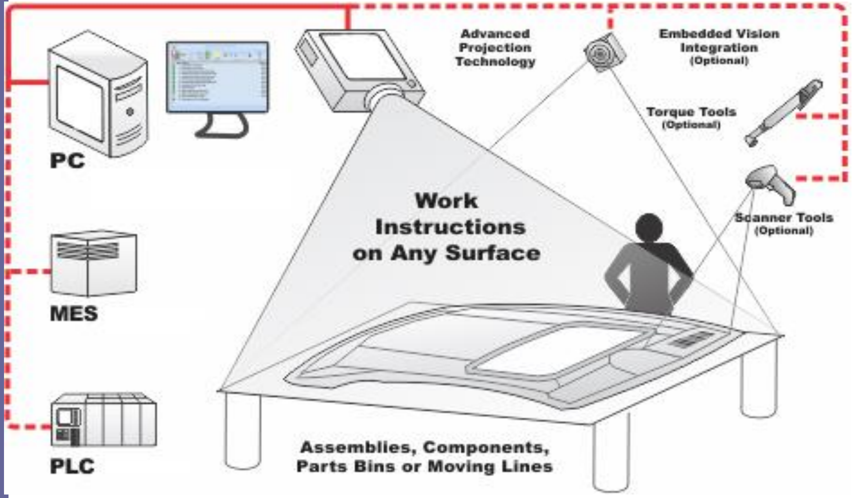


Completion rate is 2.8 times better

12 out of 14 participants prefer working with the t-predictable robot

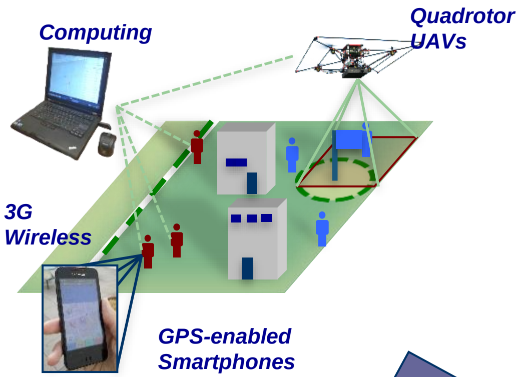
Improving Human-Robot Collaboration with AR





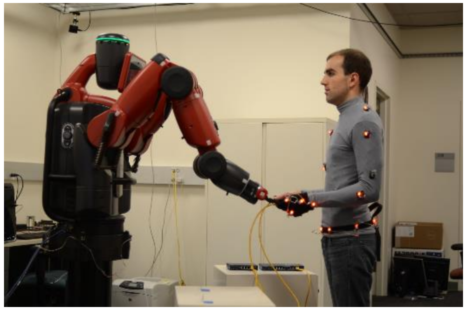
SIEMENS

Next Big Thing: Integration with AR/VR



Vehicle Control (Tomlin, Borrelli)

3D SLAM (Sastry)



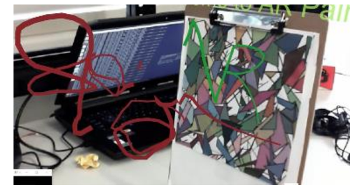
Human Collaboration (Bajcsy)

Berkeley AR Headset

Robot OS

OpenARK: Open AR toolKit

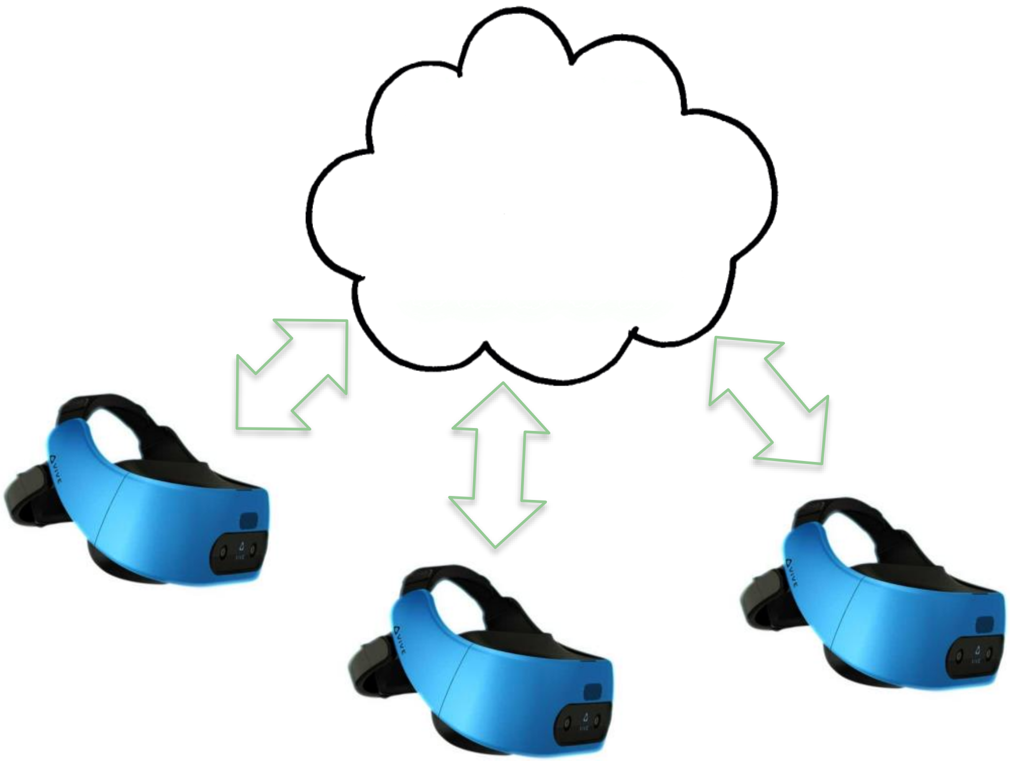
- **Sensor fusion and calibration**
  - RGB camera
  - Depth camera
  - IMU
  - Stereo display



- **3D gesture detection and modeling**
  - 98.6% accuracy on CVRR hand database

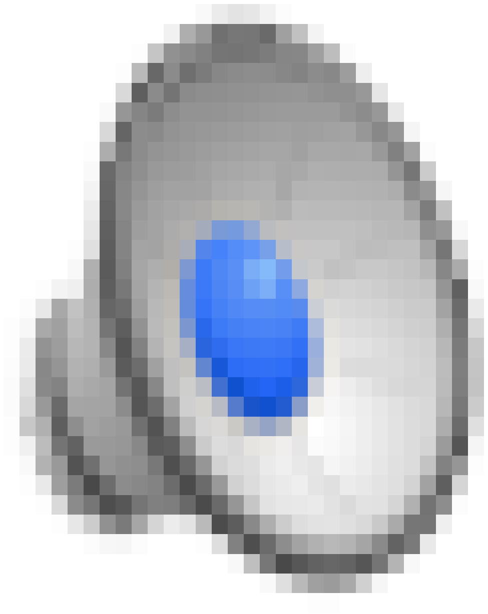
- **Room-size SLAM and 3D Reconstruction**
  - Extension from ETH OKVIS package
  - One or two cameras with synced IMU
- **Nonrigid human avatar tracking**

OpenARK Cloud in 5G Era

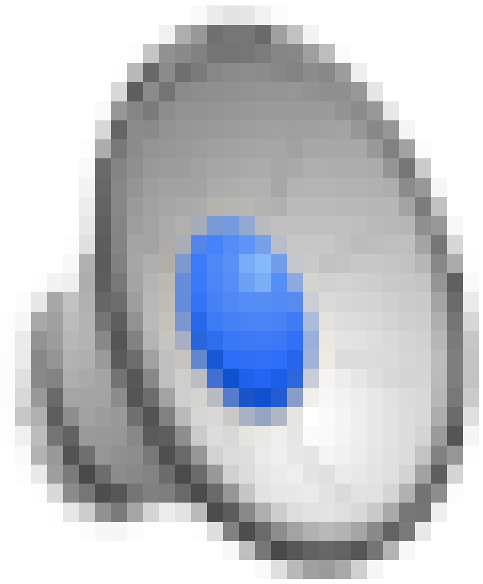


- Cloud based processing enables support for a wide variety of low power devices
- 5G Reduces latency and allows for seamless performance
- A single instance can support multiple devices
- Docker Support for easy deployment

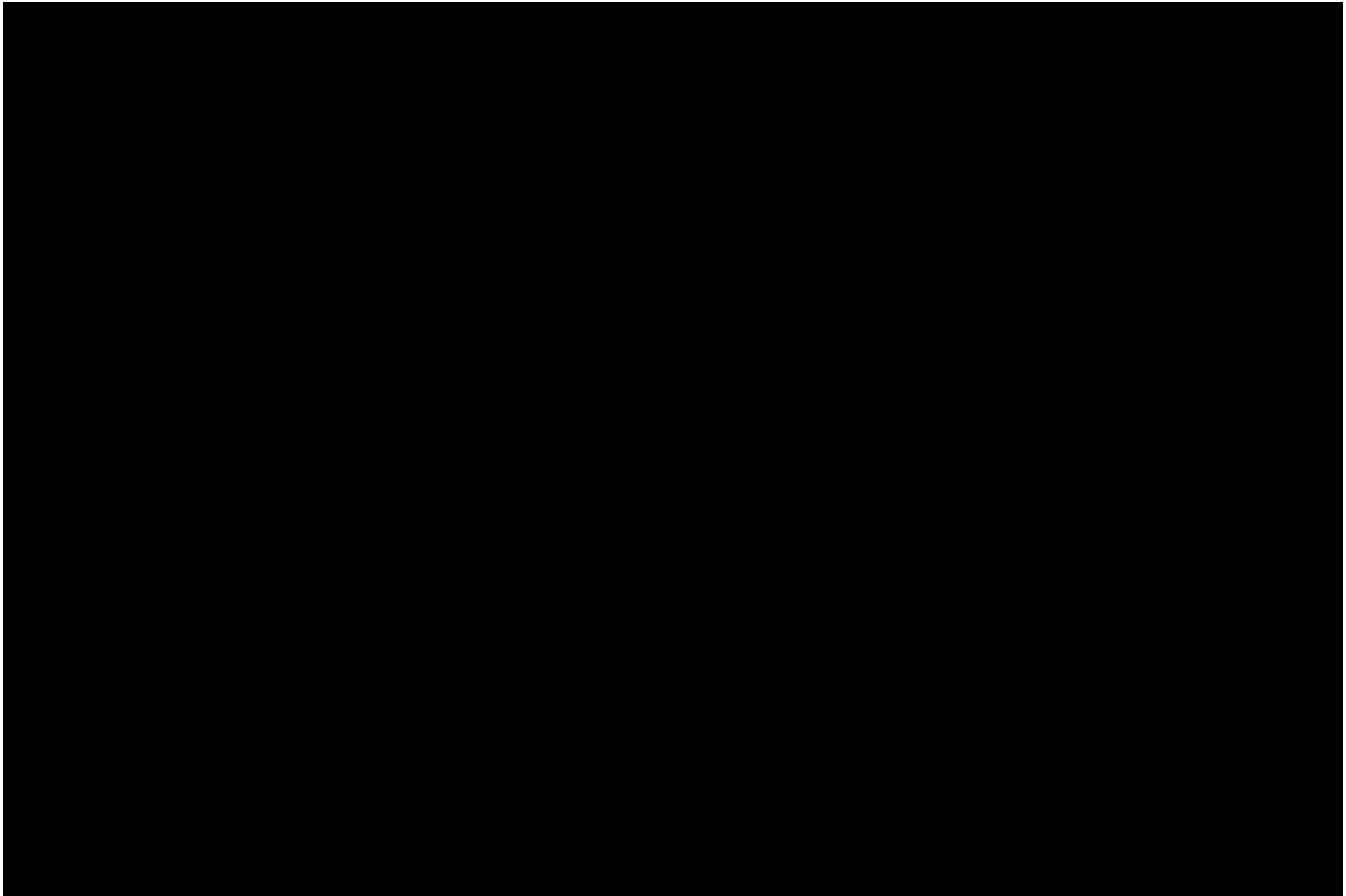
Cloud based Gesture Demo



Human Avatar Tracking Demo

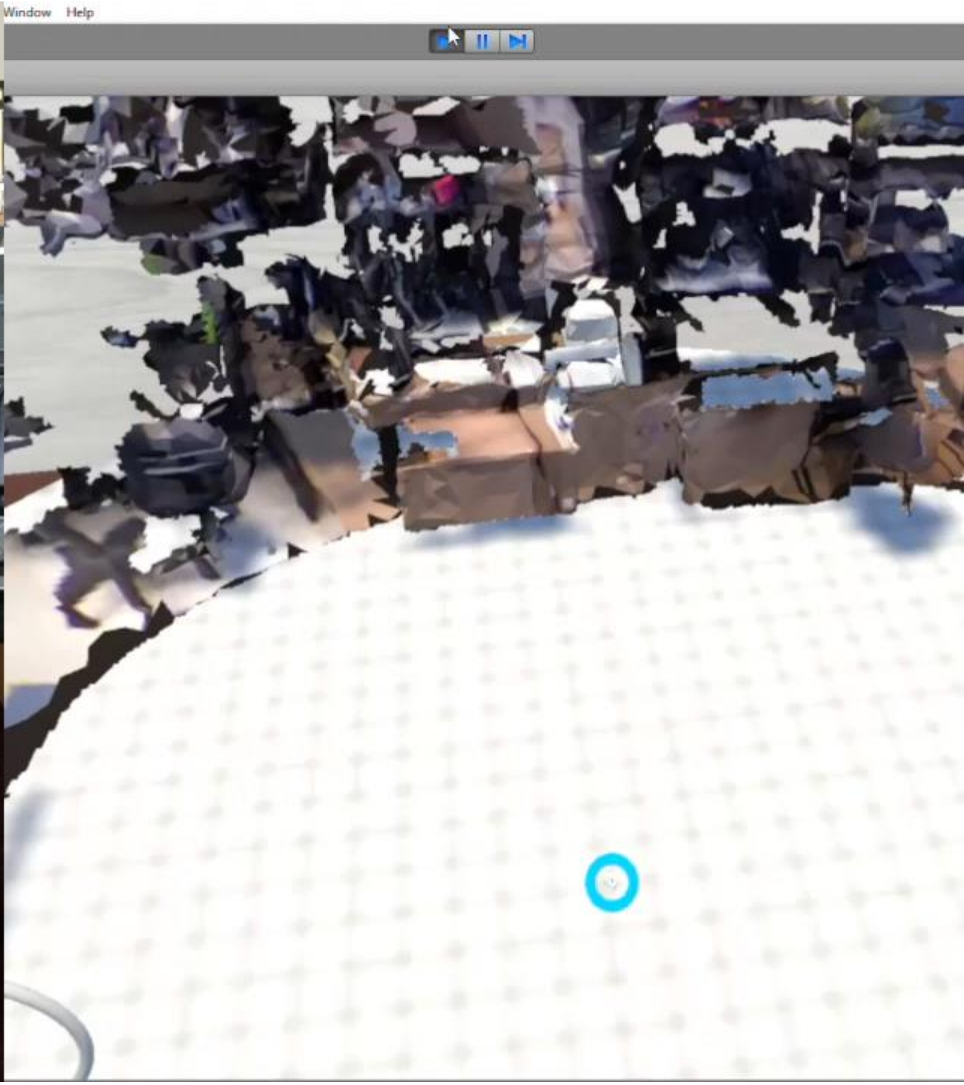


Room-Scale 3D Reconstruction Demo

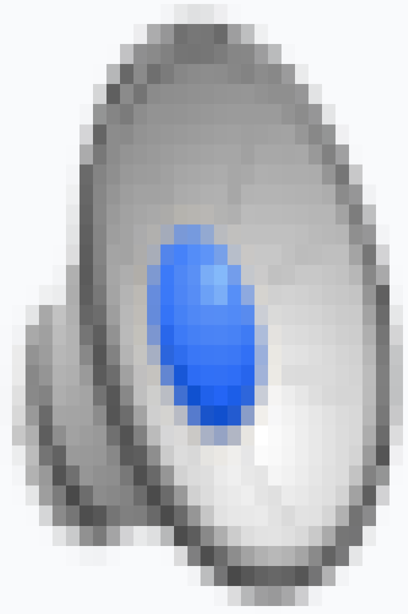


Project Highlight: ISAACS

Full System Working Demo



Pengram Remote Expert AR Demo



Health @ Home

Objective

Create and integrate novel medical technologies, delivery systems, diagnostic devices, and analysis methods that will define high-quality and cost-effective healthcare of the future.

Strategy

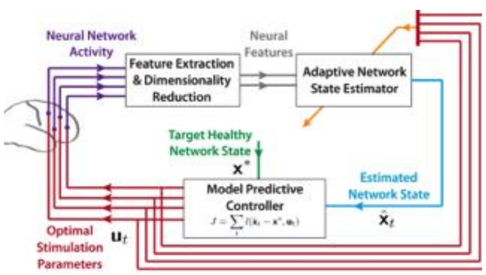
1. Health technology development,
2. Health system design, and
3. Academic-industry integration.

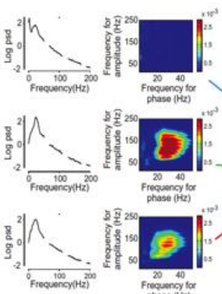
*Center for Neural Engineering & Prostheses (**CNEP**)*

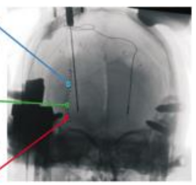
Integrates cutting-edge engineering with world-class neuroscience to **develop technology to restore sensory, motor, and cognitive function** in patients with disabling neurological conditions.

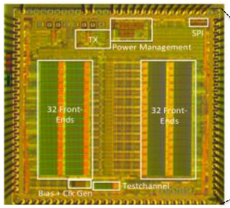
Mission is to create a multi-disciplinary environment for

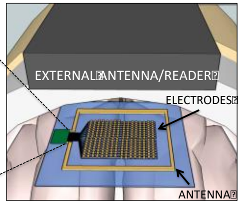
- **Educate** future neural engineers, neuroscientists and clinicians
- **Lead** scientific research and neural prosthetic technology development
- **Ensure** efficient translation of research into human












Wearable Electronics Lab
Innovative Electronics Materials and Devices at the convergence of Nanofabrication and Printing
Leveraging our strengths in novel materials, devices, and process technologies for future ultra-low-power, smart wearables
Developing a new manufacturing platform for ubiquitous electronics
Roll-to-Roll Processing
Robotics
Healthcare / Bio
New User Interfaces
Flexible electronics
Energy
Interfacing EE and chemistry through materials innovation.

The Human Intranet

An open scalable platform

- Seamlessly integrating ever-increasing number of sensor, actuation, computation, storage, communication and energy nodes located around, on, or in human body
- Acting in symbiosis with functions provided by the body itself,
- Fundamentally altering ways humans operate, and interact with physical and cyberworld
- Grand Fusion of Robotics + AR/VR + Neurotechnology