Towards robots that navigate seamlessly next to people

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M | ROBOTICS

PAUL G. ALLEN SCHOOL
OF COMPUTER SCIENCE & ENGINEERING

Successful robotics paradigm





Robots working alongside to humans



Diligent Robotics



Robots

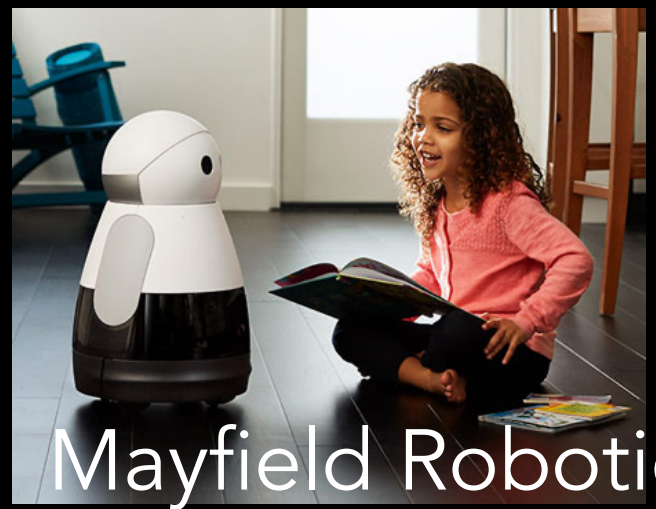

KUKA

Mobility is central


iRobot



Cruise


Mayfield Robotic

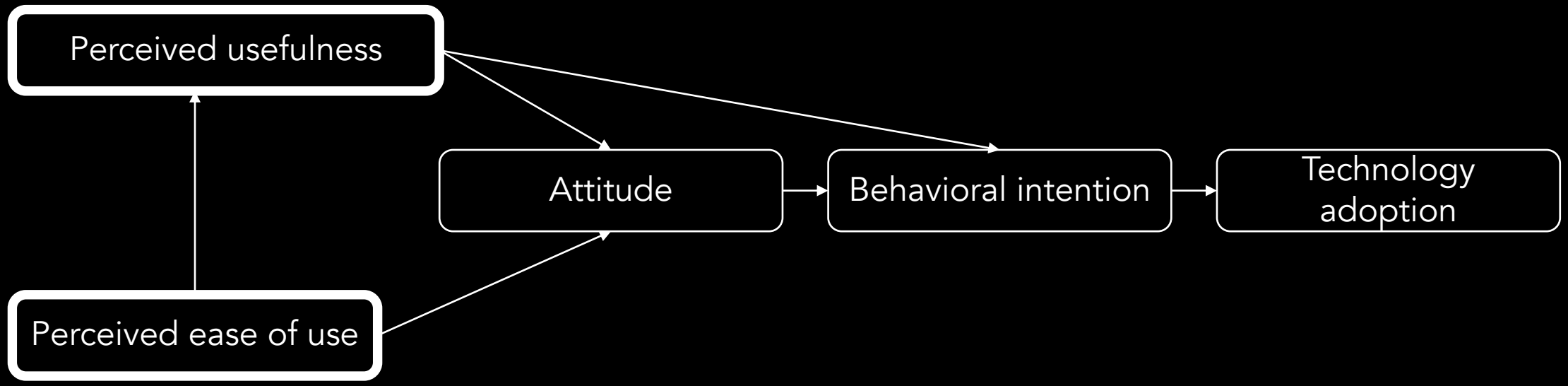
Indoor robots discomforting humans





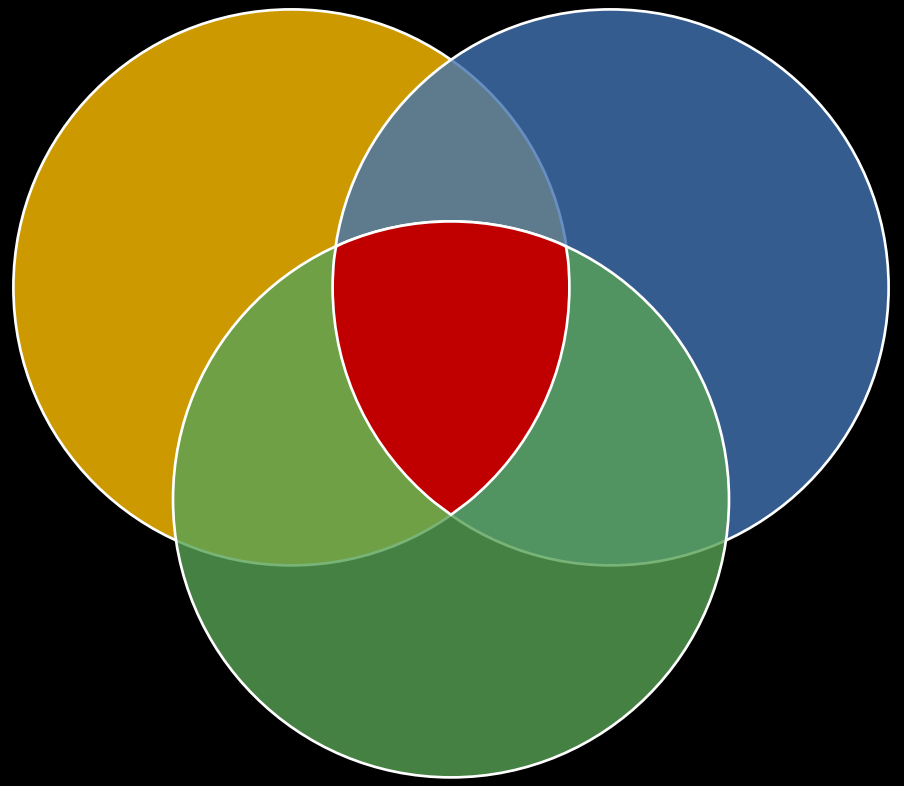
Gates Hall, Cornell University, 2015

Robot failures have consequences

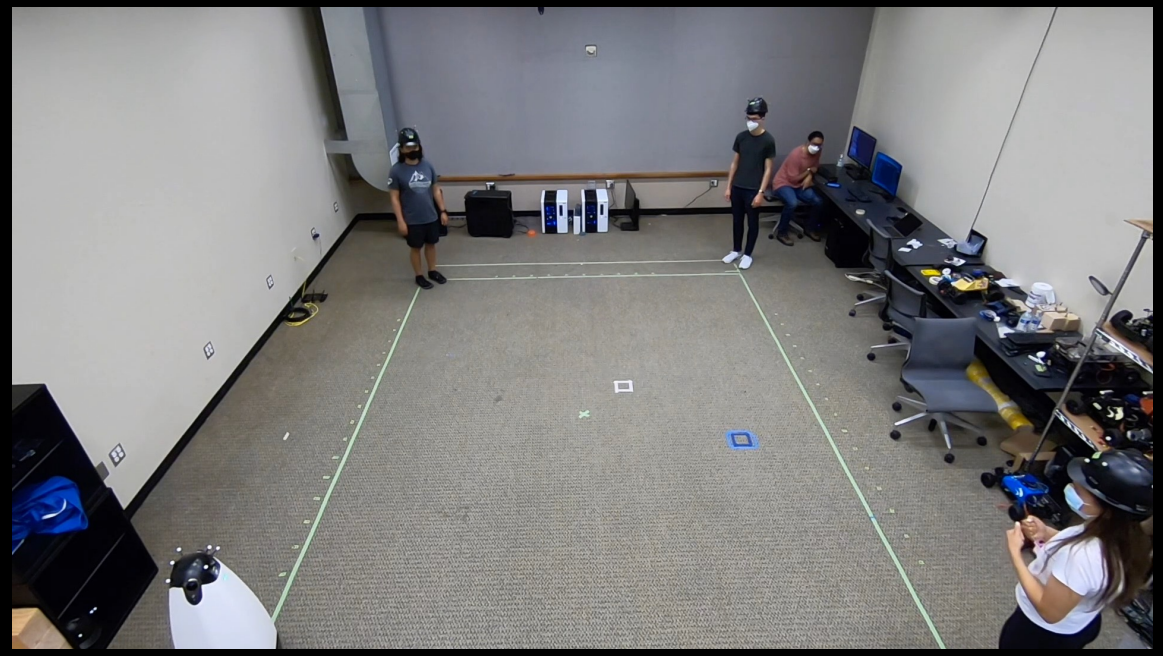


Technology acceptance model by Davis ‘89

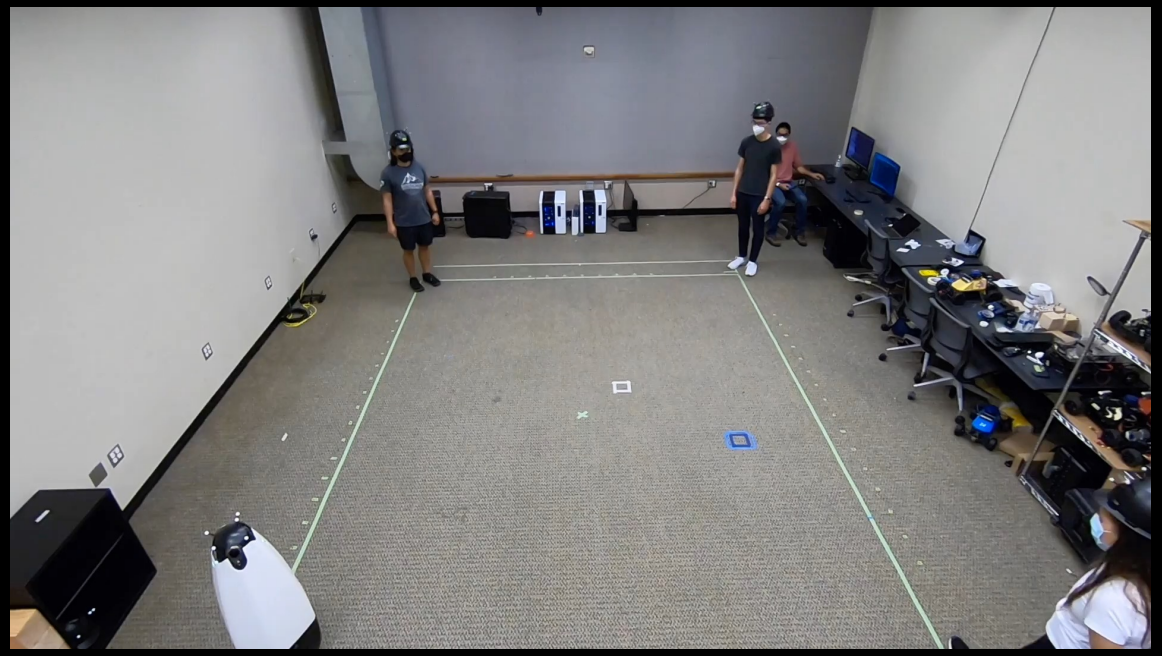
This talk: a framework for social navigation



Safe, efficient navigation in dense crowds



CADRL [Everett et al., IROS ’18]

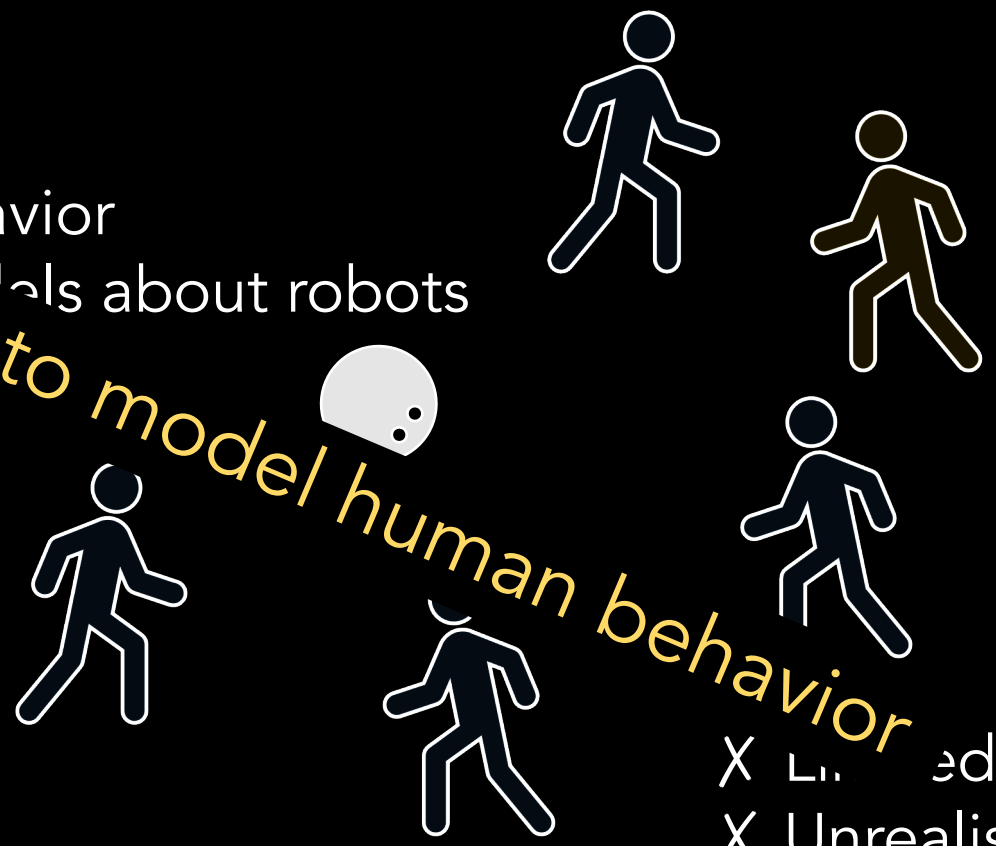


Ours [Mavrogiannis et al. RAL ’23, ICRA ’23]

The problem

The problem: Navigation next to humans

- ✗ Large space of behavior
- ✗ Limited mental models about robots
- ✗ No rules
- ✗ Social conventions



- ✗ Limited datasets
- ✗ Unrealistic simulators

Progress in human motion prediction

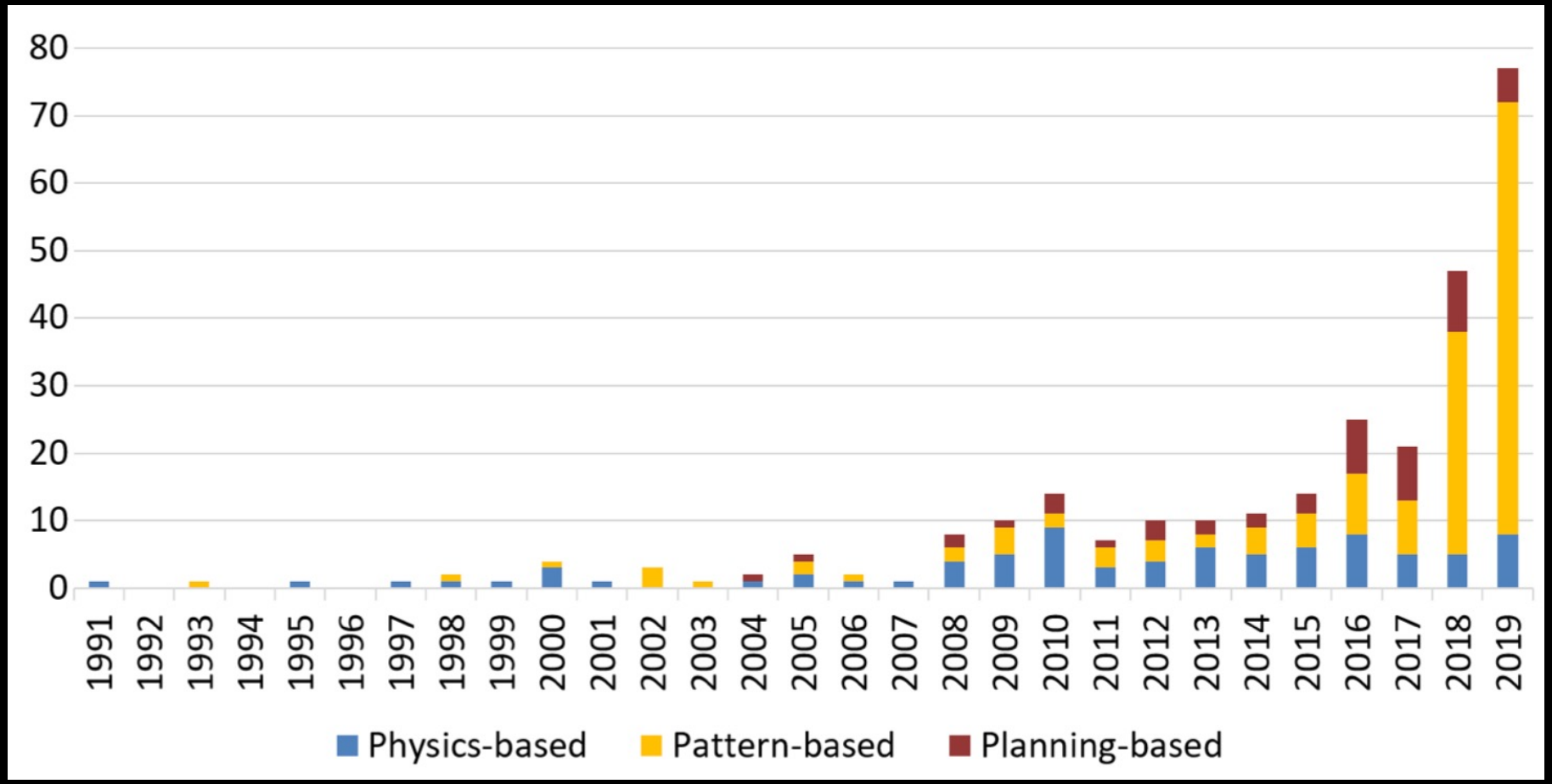


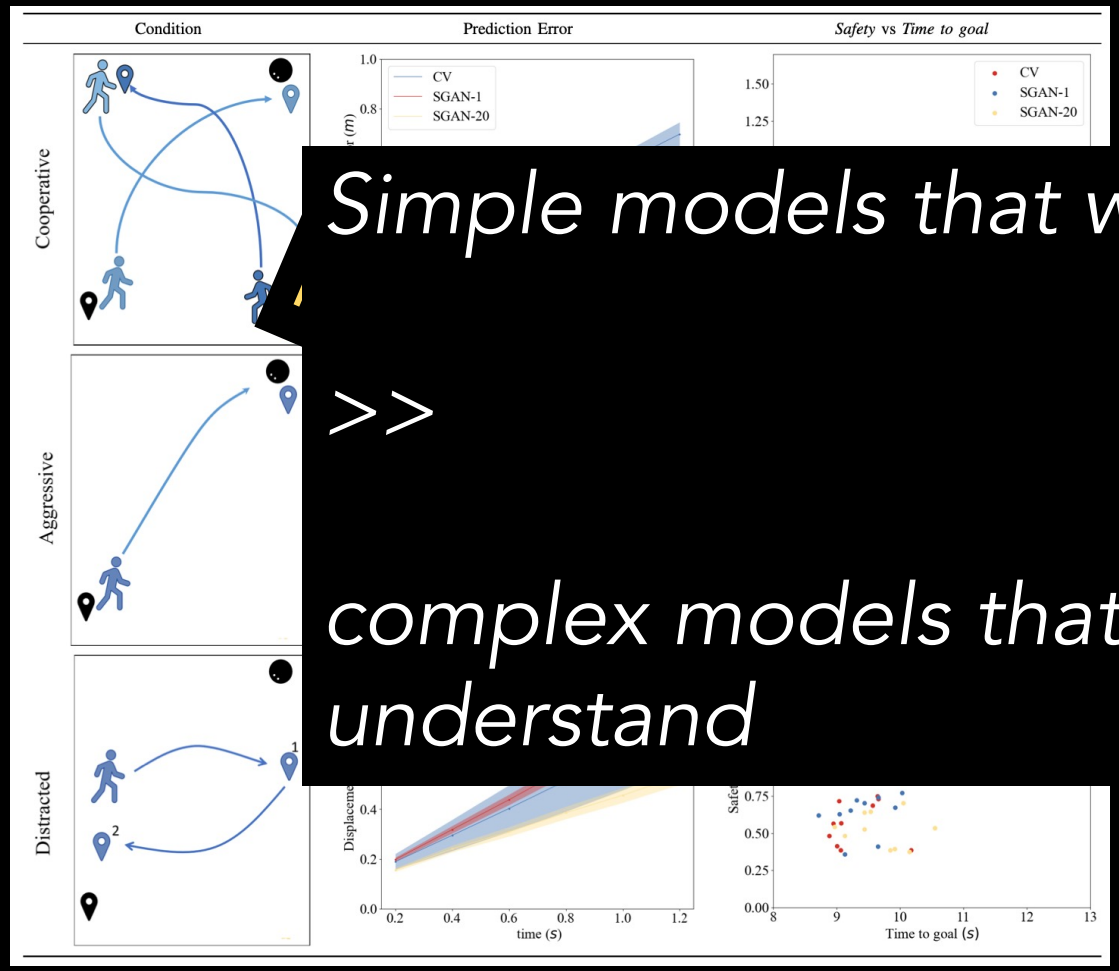
Figure from Rudenko et al. IJRR 2020.

Better prediction ⇒ better navigation?

Cooperative

Poddar et al. From crowd motion prediction to robot navigation in crowds. arXiv preprint 2023. Under review for IROS.

Better prediction ⇒ better navigation?



MPC w/ CV ~ MPC 1/ S-GAN

Simple models that we understand well

ns by

_ '20

>>

complex models that we don't understand

Poddar et al. From crowd motion prediction to robot navigation in crowds. arXiv preprint 2023. Under review for IROS.

Functionality

How do humans do it?



Wolfinger ‘95

Pedestrian interaction is inherently complex yet observably ordered. For order to be possible, people must behave like competent pedestrians and must expect copresent others to act accordingly. Although many researchers have examined pedestrian behavior, few have considered exactly how pedestrians develop and sustain the expectation that others will indeed behave like competent pedestrians. Using ethnographic data, the author shows how these expectations emerge in the specific practices that comprise pedestrian behavior. Various researchers have attributed pedestrian order to the existence of a tacit contract between users of public space. The author's findings extend the implications of this work by explicating the social and collaborative processes by which users of public space come to trust each other to act like competent pedestrians.

PASSING MOMENTS

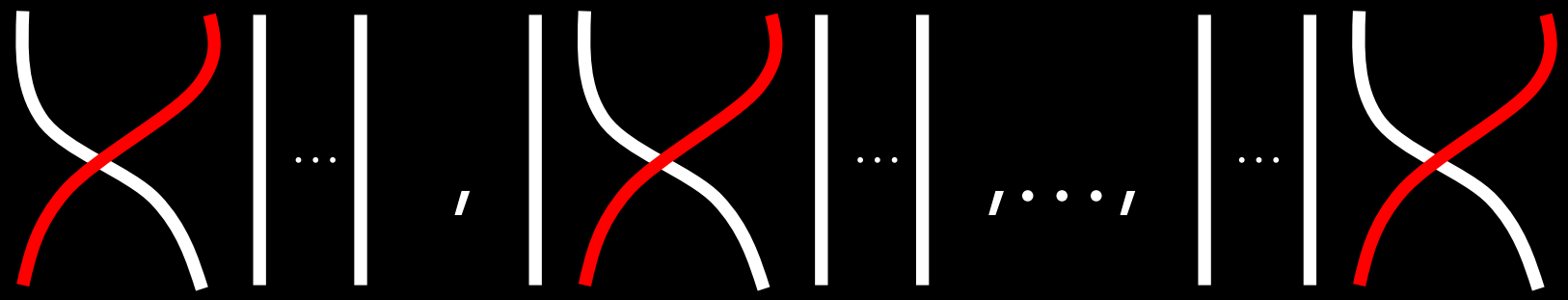
Some Social Dynamics of Pedestrian Interaction

How can we represent passing?

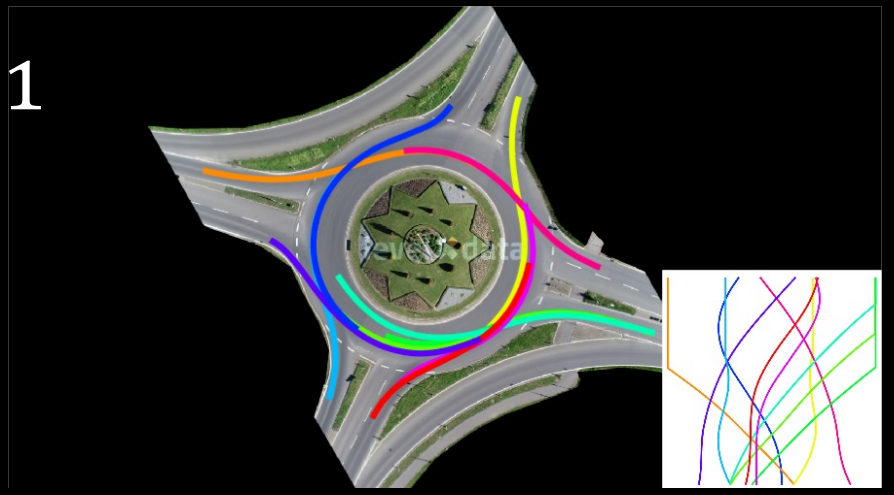


Γαϊτανάκι (gaitanaki, “maypole dance”)
https://youtu.be/0wpTPyUCA3s

How can we represent passing?

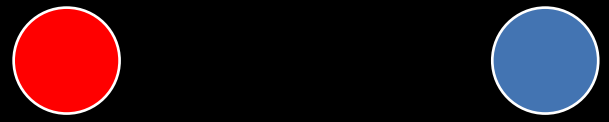


Artin. Theory of Braids. Annals of Mathematics. 1947



IROS ’17, IJRR ’19, IJRR ’21, ICRA ’22

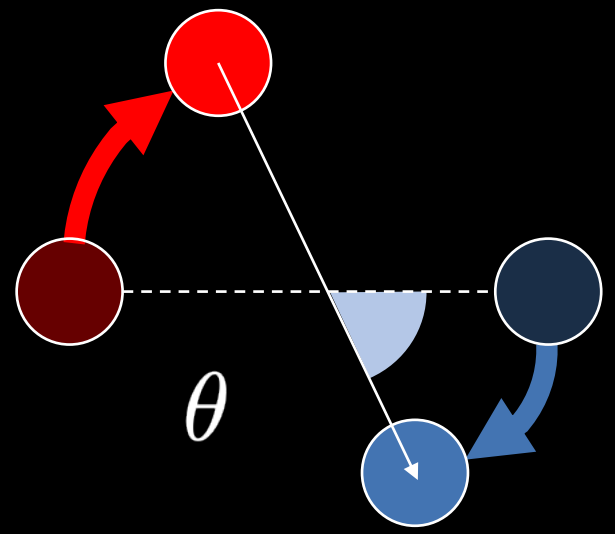
Passing as rotation



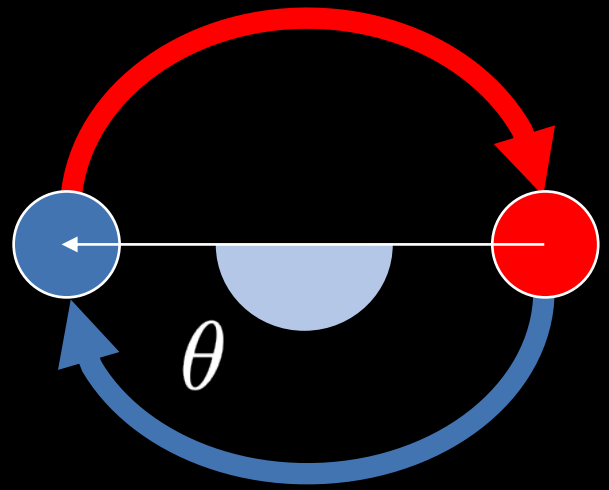
Passing as rotation



Passing as rotation



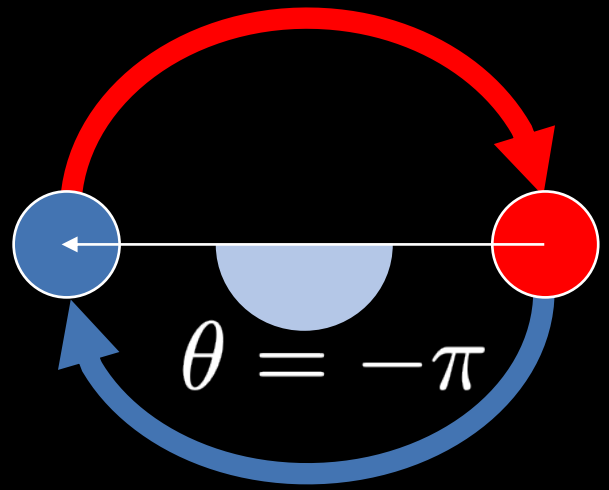
Passing as rotation



Passing as rotation

$$\lambda = \frac{1}{2\pi} \int d\theta$$

Winding number



Progress

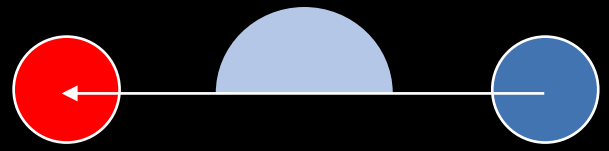
Side

$$\lambda = -0.5$$

Passing as rotation

$$\lambda = \frac{1}{2\pi} \int d\theta$$

Winding number



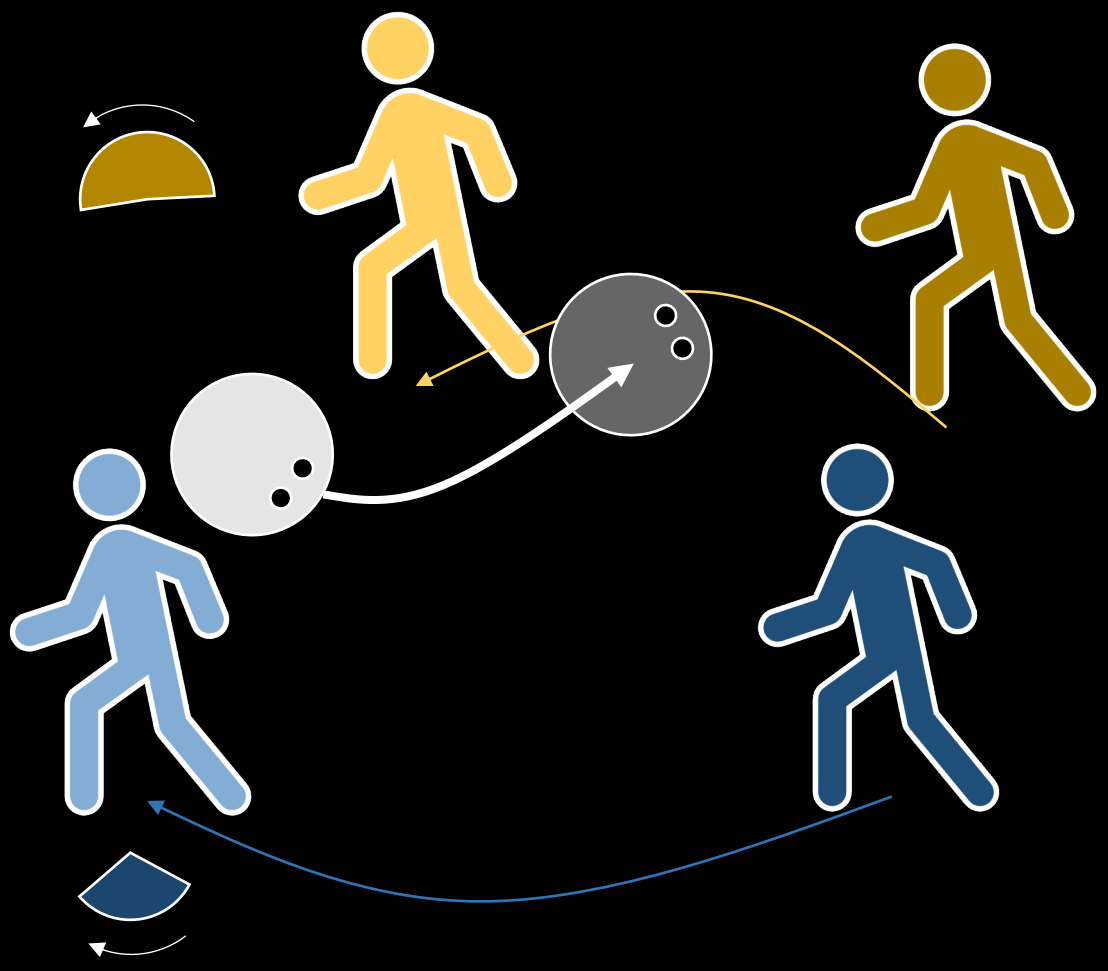
$\theta = \pi$

Progress

Side

$$\lambda = +0.5$$

A cost that expedites passing



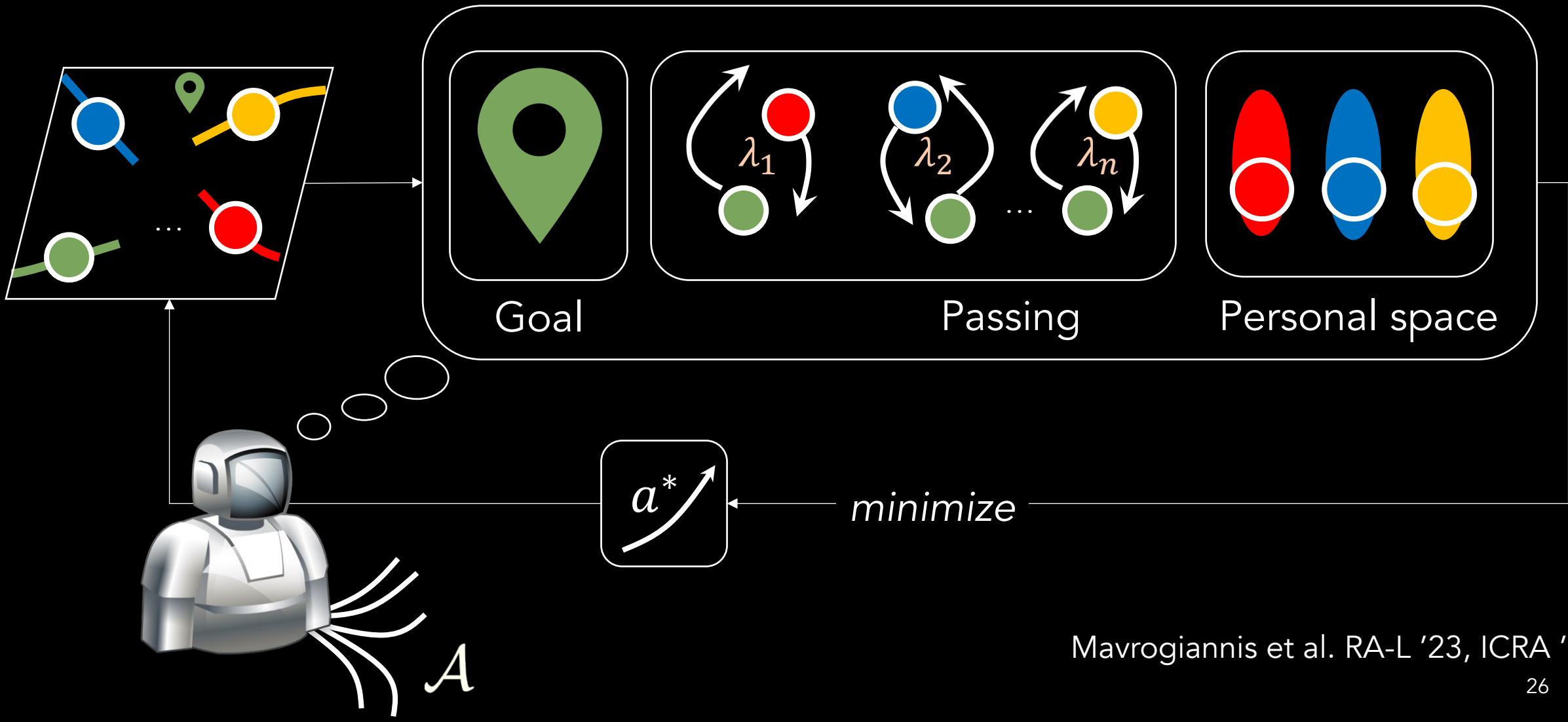
*Motivate actions that increase passing progress**

$$\mathcal{J} = -\frac{1}{n}\sum_{i=1}^{n} \lambda_i^2$$

**under a prediction about users' future motion*

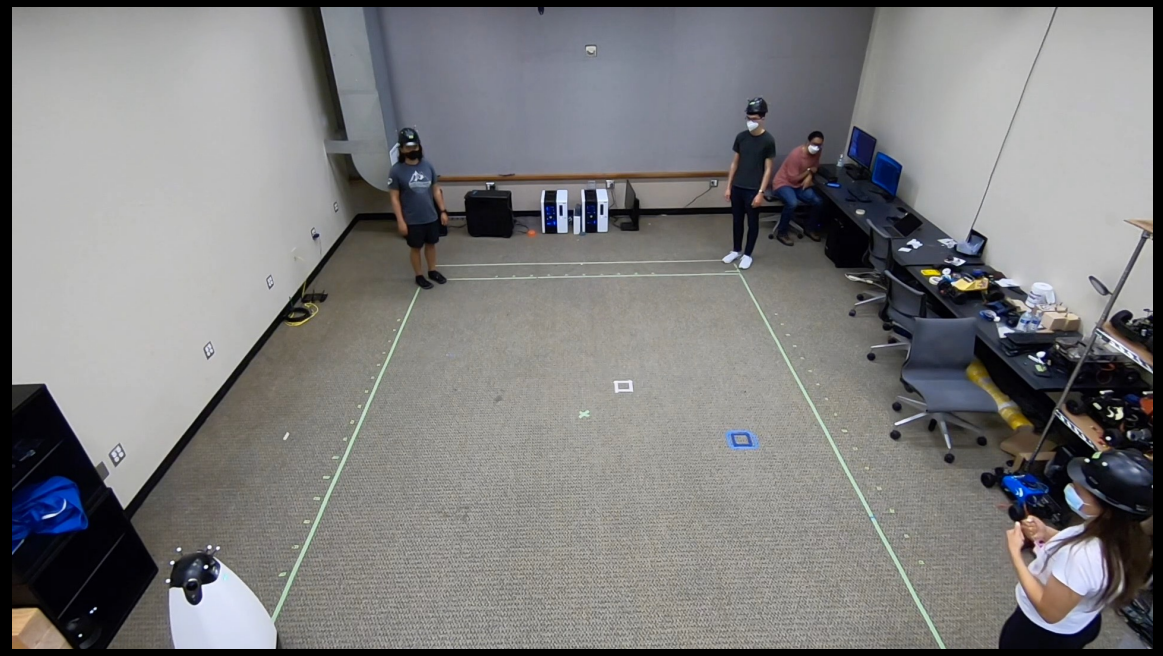
Expedite passing, respect personal space

**Constant velocity prediction!*

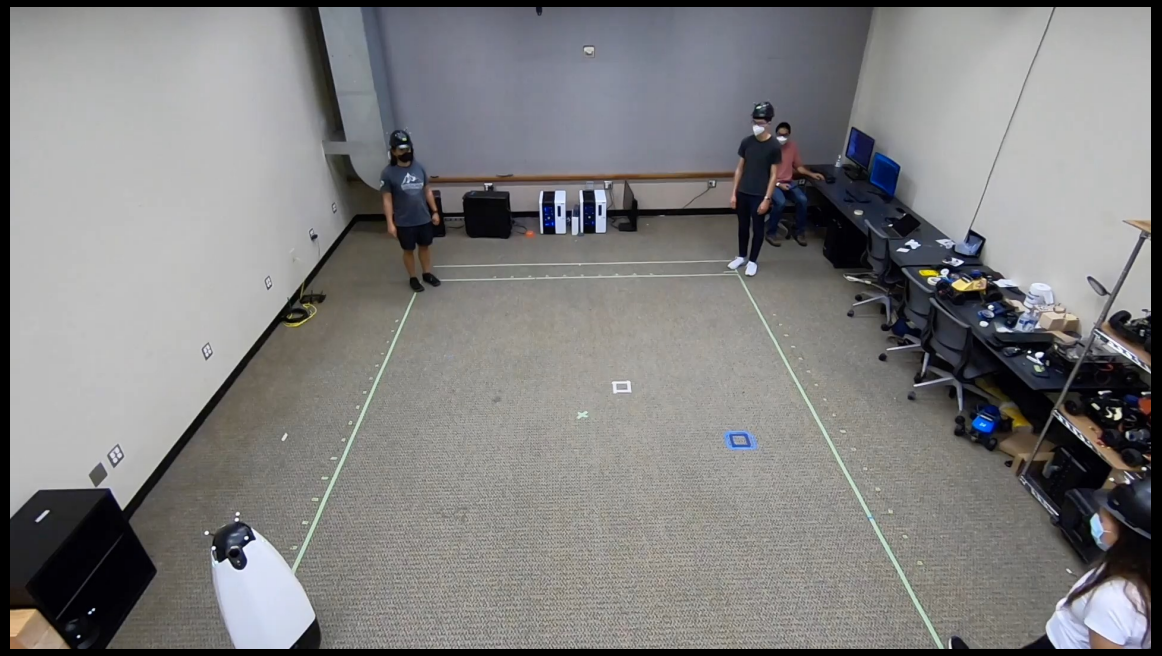


Mavrogiannis et al. RA-L '23, ICRA '23

Safe, efficient navigation in dense crowds



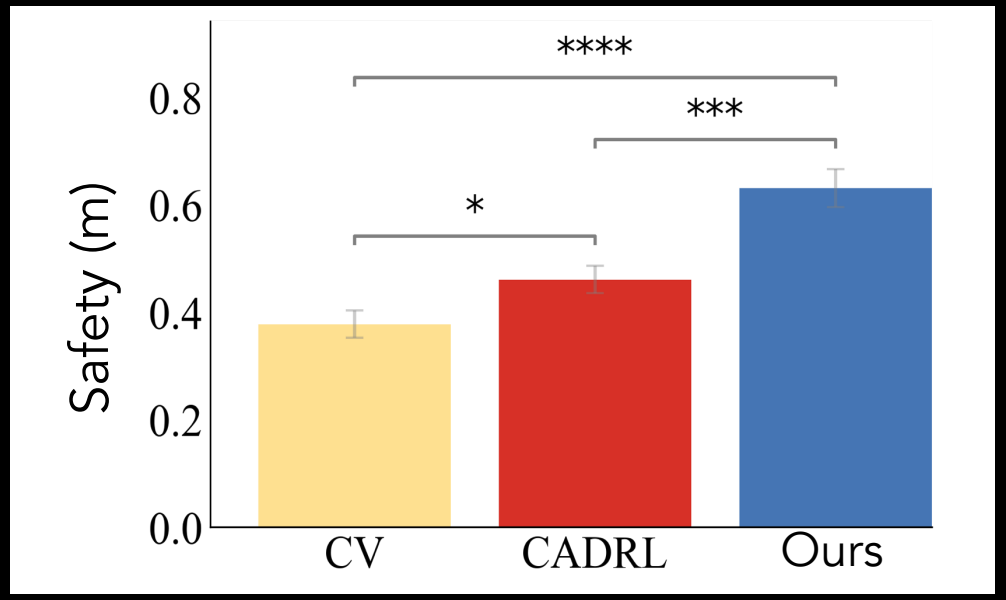
CADRL [Everett et al., IROS ’18]



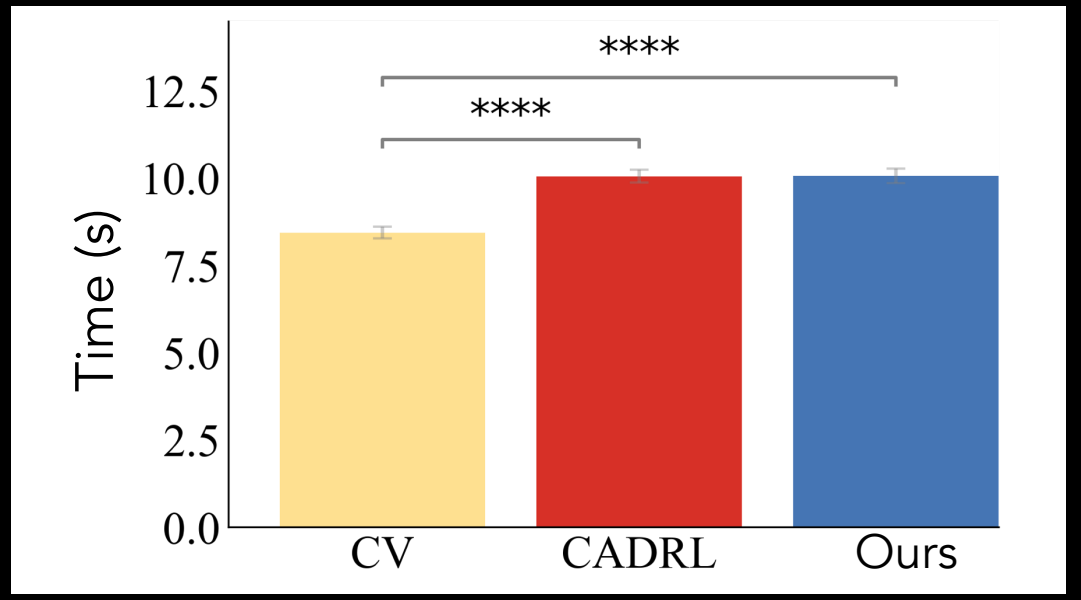
Ours [Mavrogiannis et al. RAL ’23, ICRA ’23]

Safe, efficient navigation in dense crowds

Higher is better



Lower is better



Summary & open problems

Domain knowledge & math insights empower simple models

Scaling requires deeper understanding of humans

Beyond Safety & Efficiency

Understanding users' perceptions

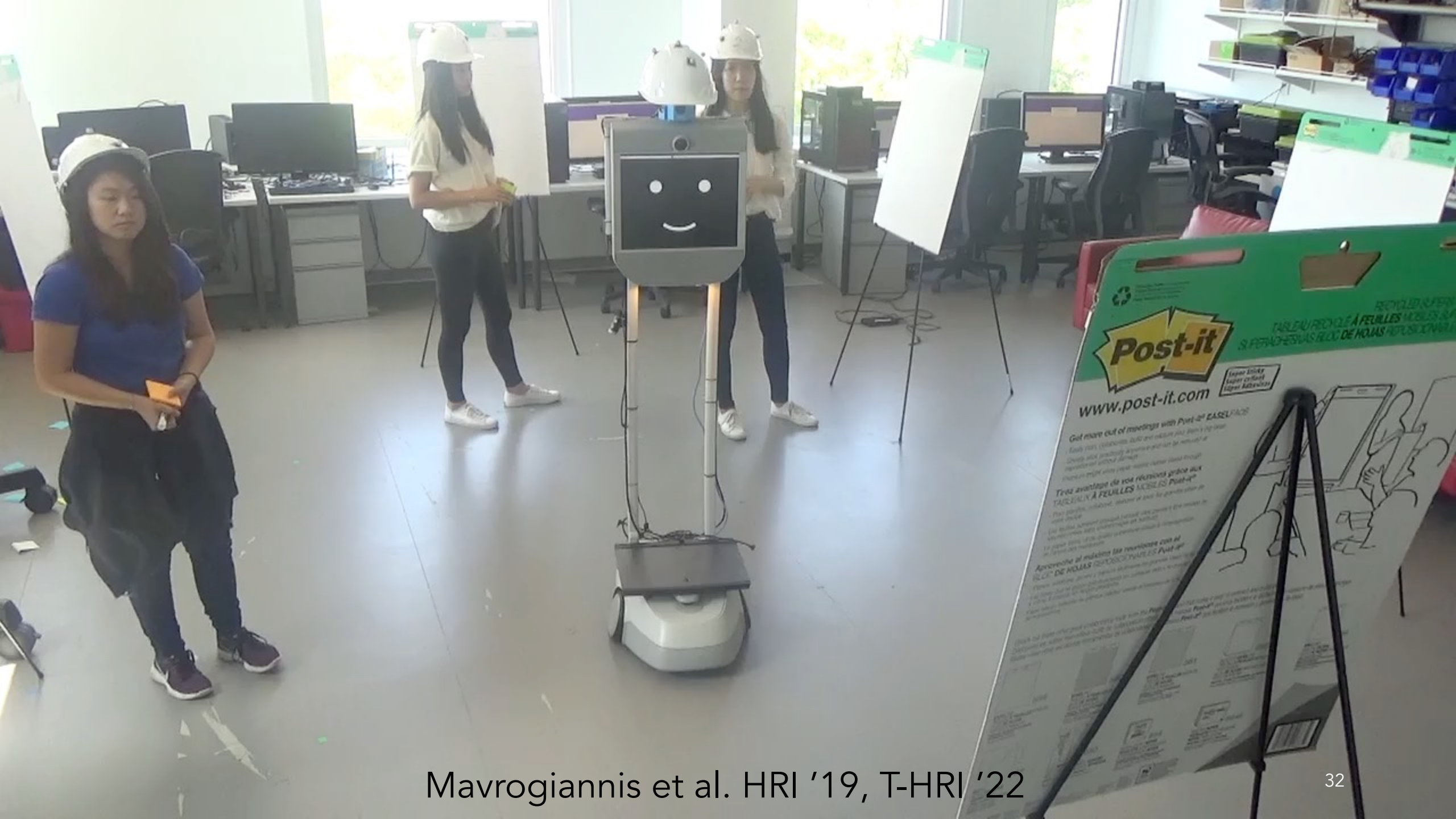
Study design considerations

Natural walking

Crowded space

Challenging interactions





Mavrogiannis et al. HRI ’19, T-HRI ’22

Within subjects, 3 conditions



Ours
[Mavrogiannis et al., ‘18]



ORCA
[Van den Berg et al., ‘09]

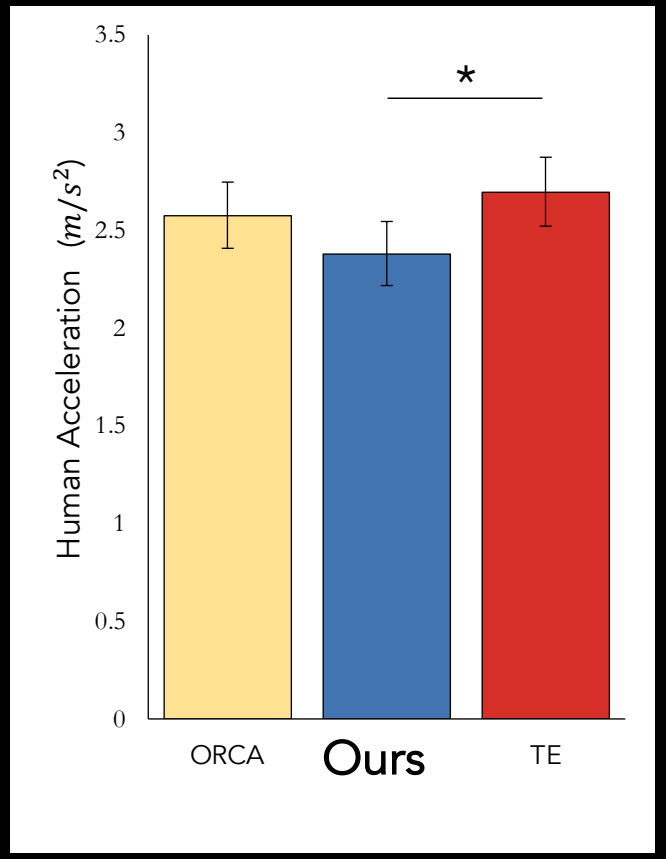


Teleoperation (TE)

Mavrogiannis et al. HRI ‘19, T-HRI ‘22

105 users walked comfortably next to ours

Lower is better

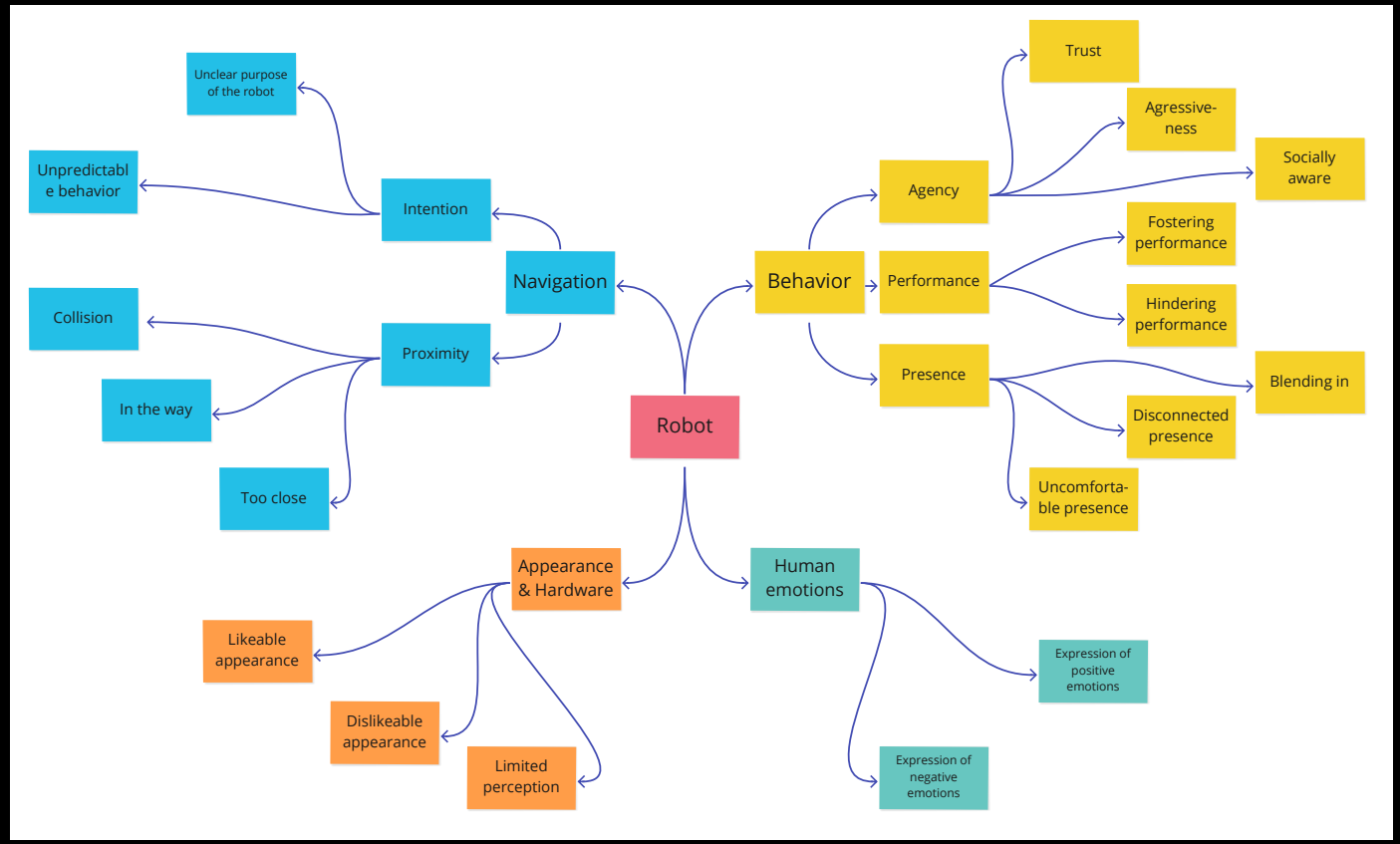


Lower acceleration

Users were less disturbed by the robot

Mavrogiannis et al. HRI ‘19, T-HRI ‘22

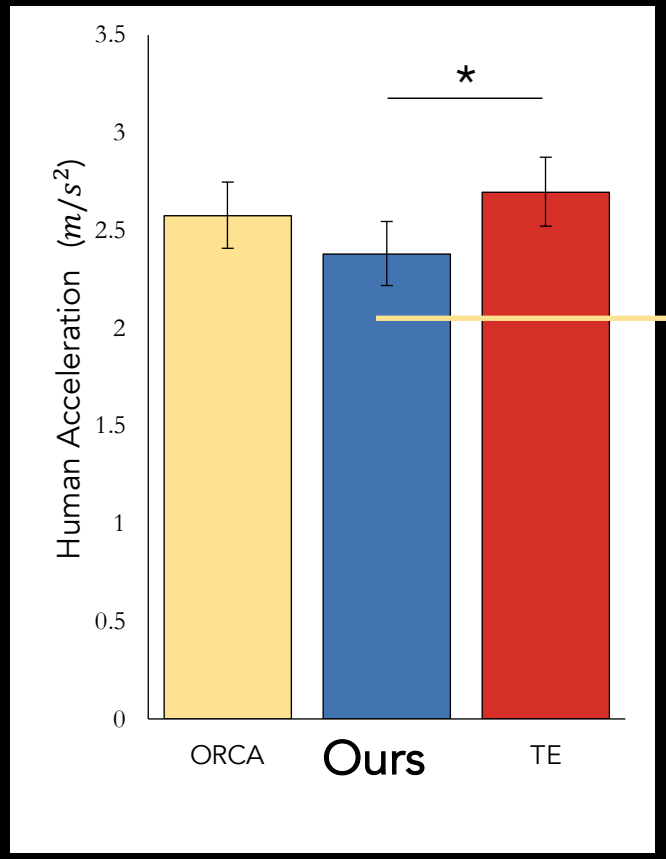
Qualitative analysis of short responses



Mavrogiannis et al. HRI ‘19, T-HRI ‘22

105 users walked comfortably next to ours

Lower is better



"I barely noticed the robot when I was performing the tasks" (Ours)

"I had no idea what the robot was doing" (TE)

"I felt the robot was in my personal space" (ORCA)

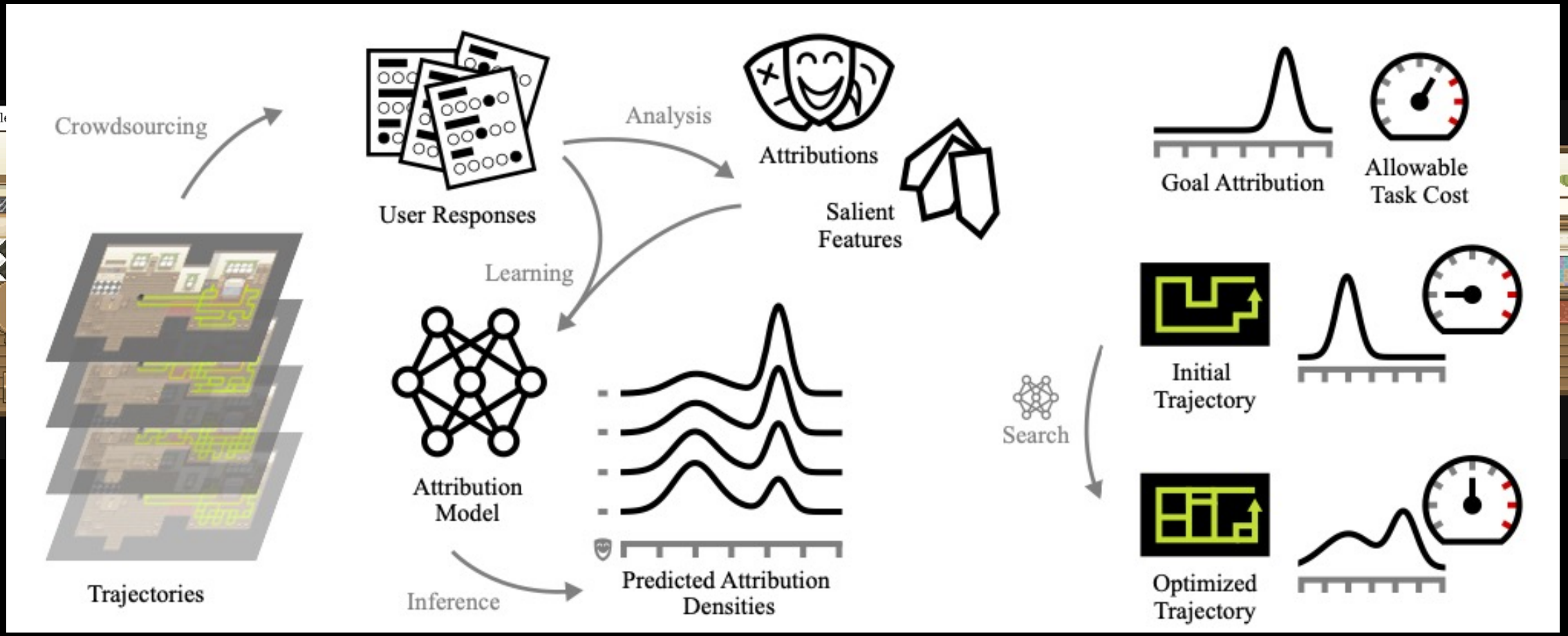
Mavrogiannis et al. HRI '19, T-HRI '22

There is more to human perceptions…



Mavrogiannis et al. HRI ‘19, T-HRI ‘22

Perception-aware motion generation



Walker et al. CoRL ’21

Many additional challenges

Qualitative↔quantitative

User-centered benchmarking

Core Challenges of Social Robot Navigation: A Survey

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JEAN OH, The Robotics Institute, Carnegie Mellon University, USA

Robot navigation in crowded public spaces is a complex task that requires addressing a variety of engineering and human factors challenges. These challenges have motivated a great amount of research resulting in important developments for the fields of robotics and human-robot interaction over the past three decades. Despite the significant progress and the massive recent interest, we observe a number of significant remaining challenges that prohibit the seamless deployment of autonomous robots in crowded environments. In this survey article, we organize existing challenges into a set of categories related to broader open problems in robot planning, behavior design, and evaluation methodologies. Within these categories, we review past work, and offer directions for future research. Our work builds upon and extends earlier survey efforts by a) taking a critical perspective and diagnosing fundamental limitations of adopted practices in the field and b) offering constructive feedback and ideas that could inspire research in the field over the coming decade.

CCS Concepts: • **Computing methodologies** → **Simulation evaluation**; **Reinforcement learning**; **Robotic planning**; • **Computer systems organization** → **Robotics**; **Robotic control**; • **Human-centered computing** → *User studies.*

Additional Key Words and Phrases: Social robot navigation, motion planning, motion prediction, multiagent systems, social robotics, benchmarking

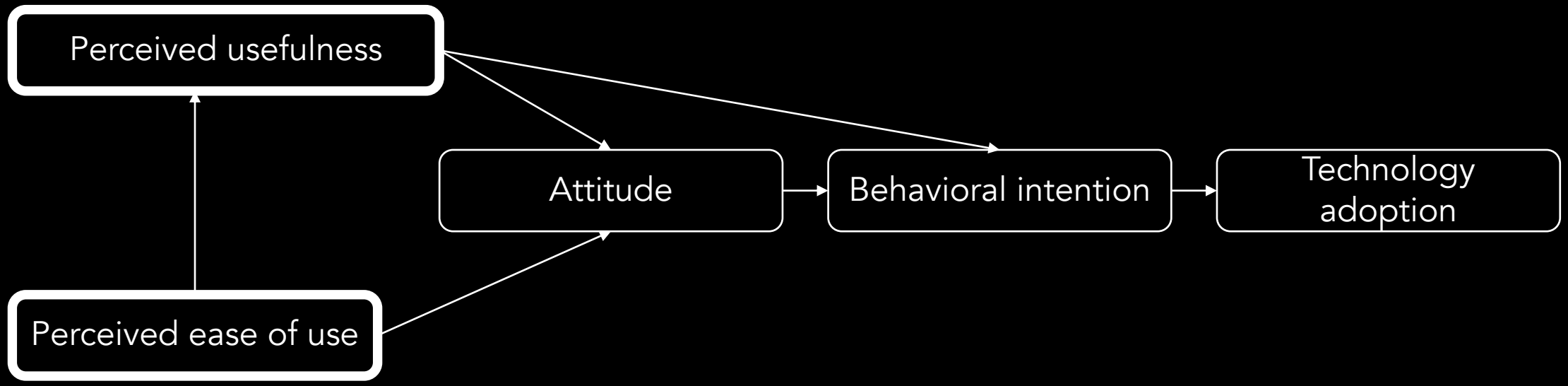
Mavrogiannis et al. T-HRI 2023

Handling failures





Robot failures have consequences



Technology acceptance model by Davis ‘89

Failures are an opportunity

Leverage human feedback to scale performance

- Recovery & Learning

Adjust user expectations

- Communicate robot capabilities & limitations



Nanavati, Walker et al. HRI ‘22

Navigation with human help

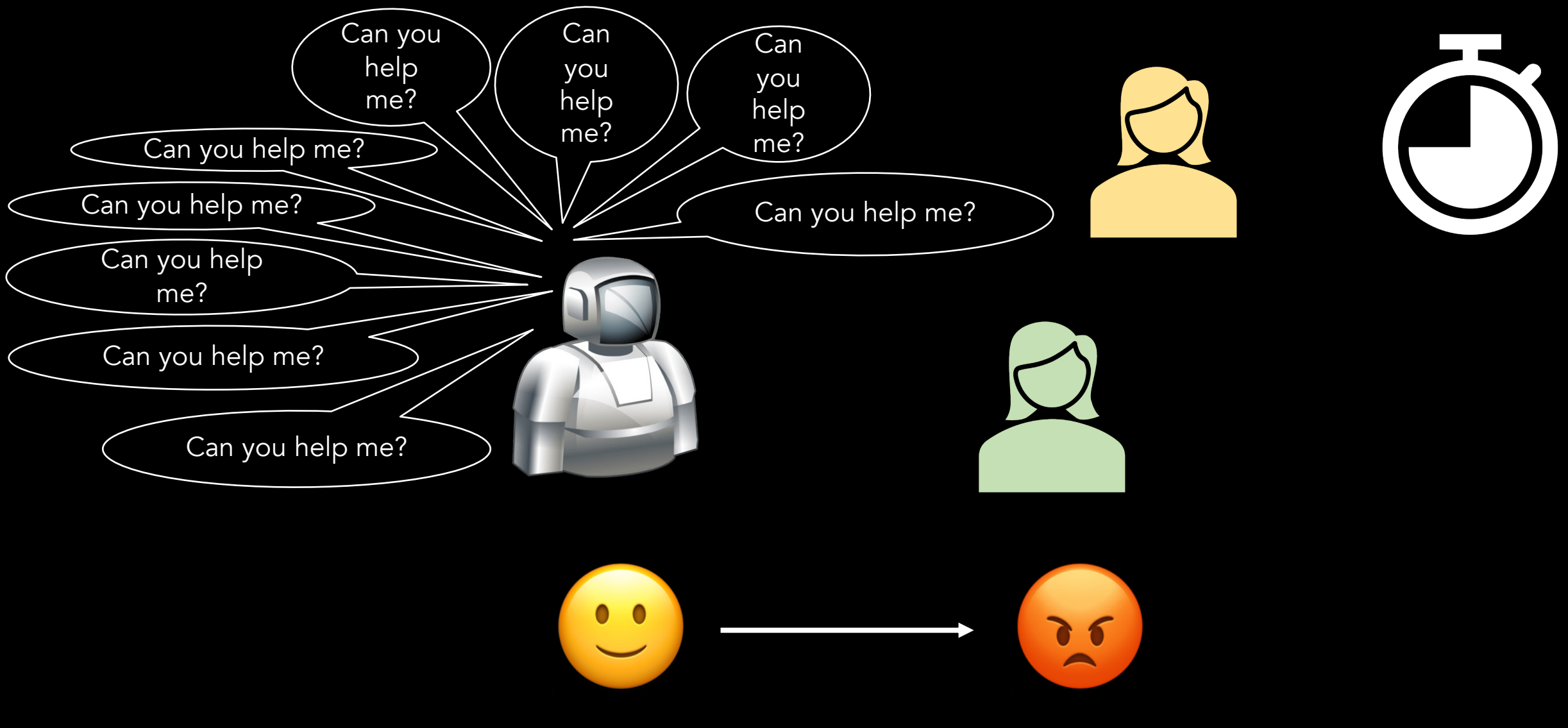




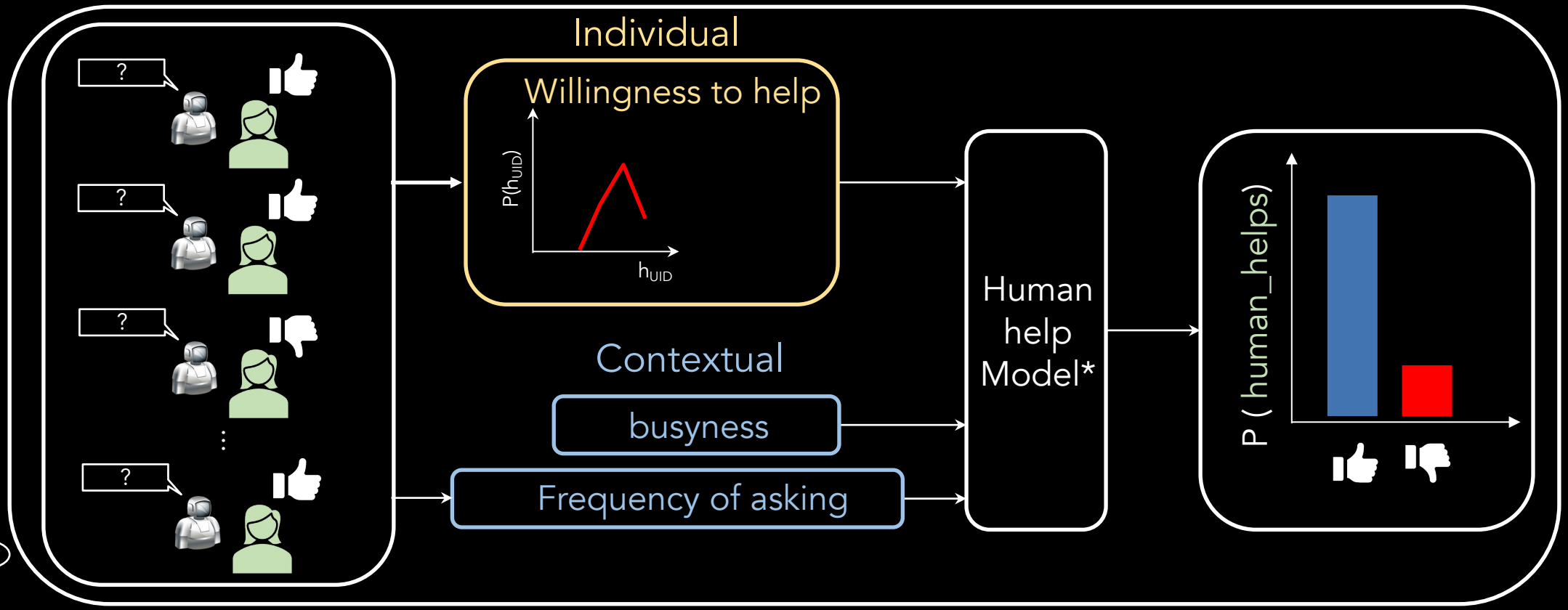


Nanavati, Walker et al. HRI ‘22

But engaging users in the wild is tricky…



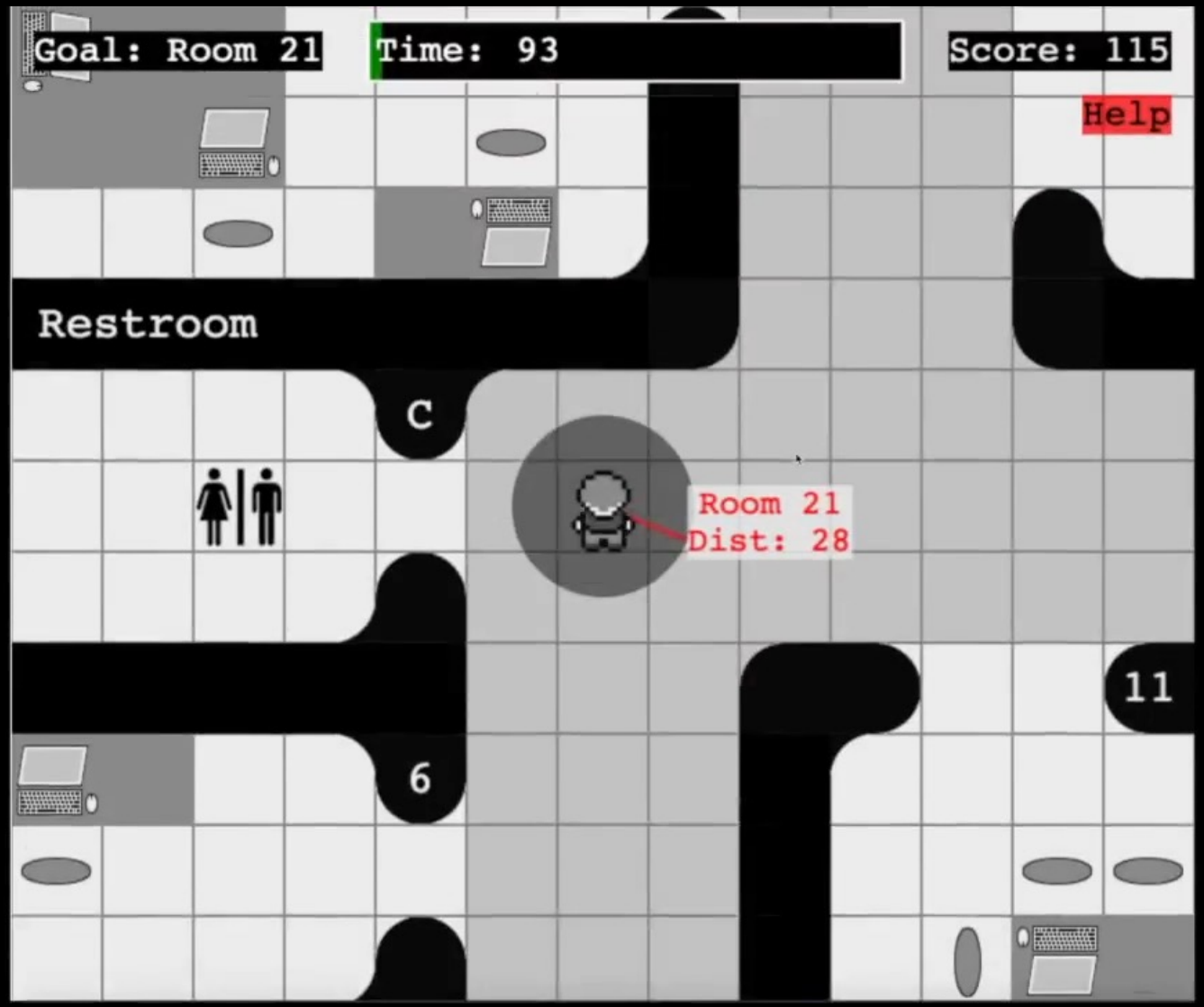
Predicting success of help request



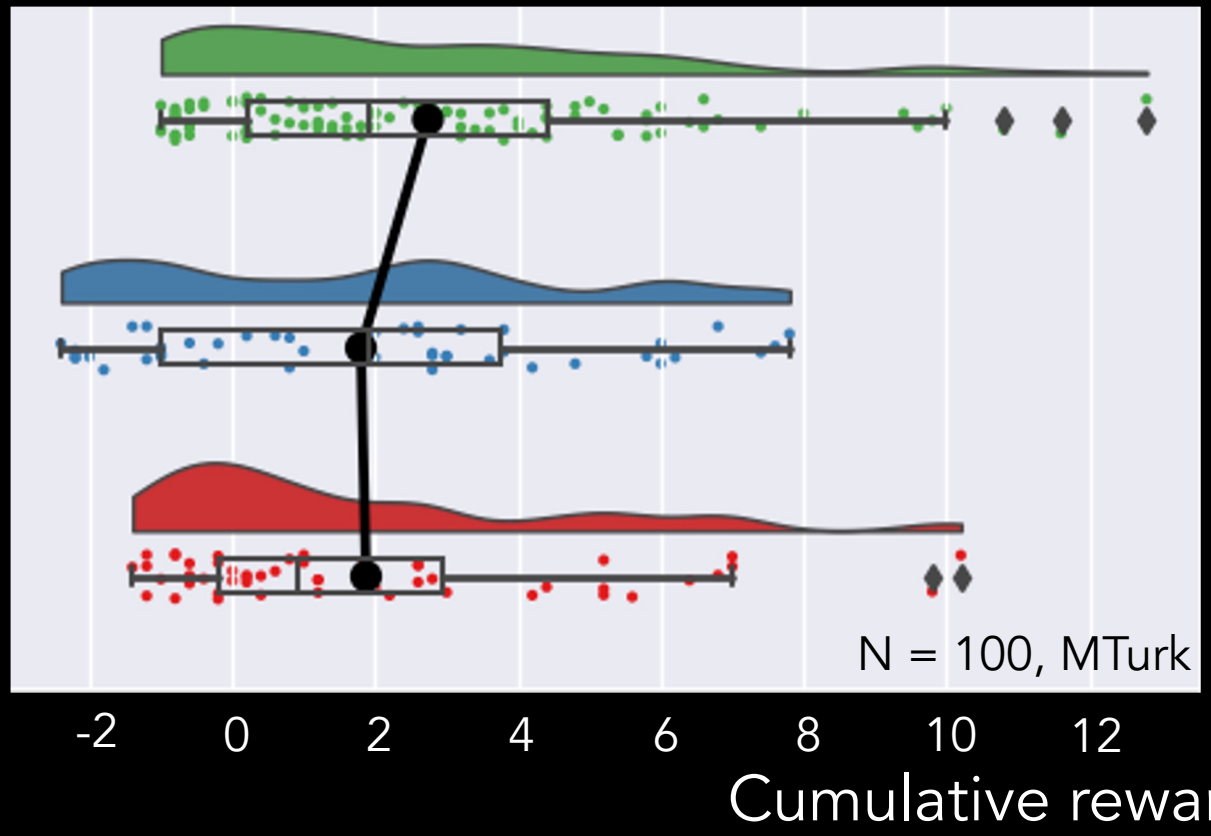
*Generalized Linear Mixed Models (GLMM)

Nanavati et al. RSS '21

Planning with the model of human help



Planning effective help requests



"[Hybrid] was politer [than Individual]"

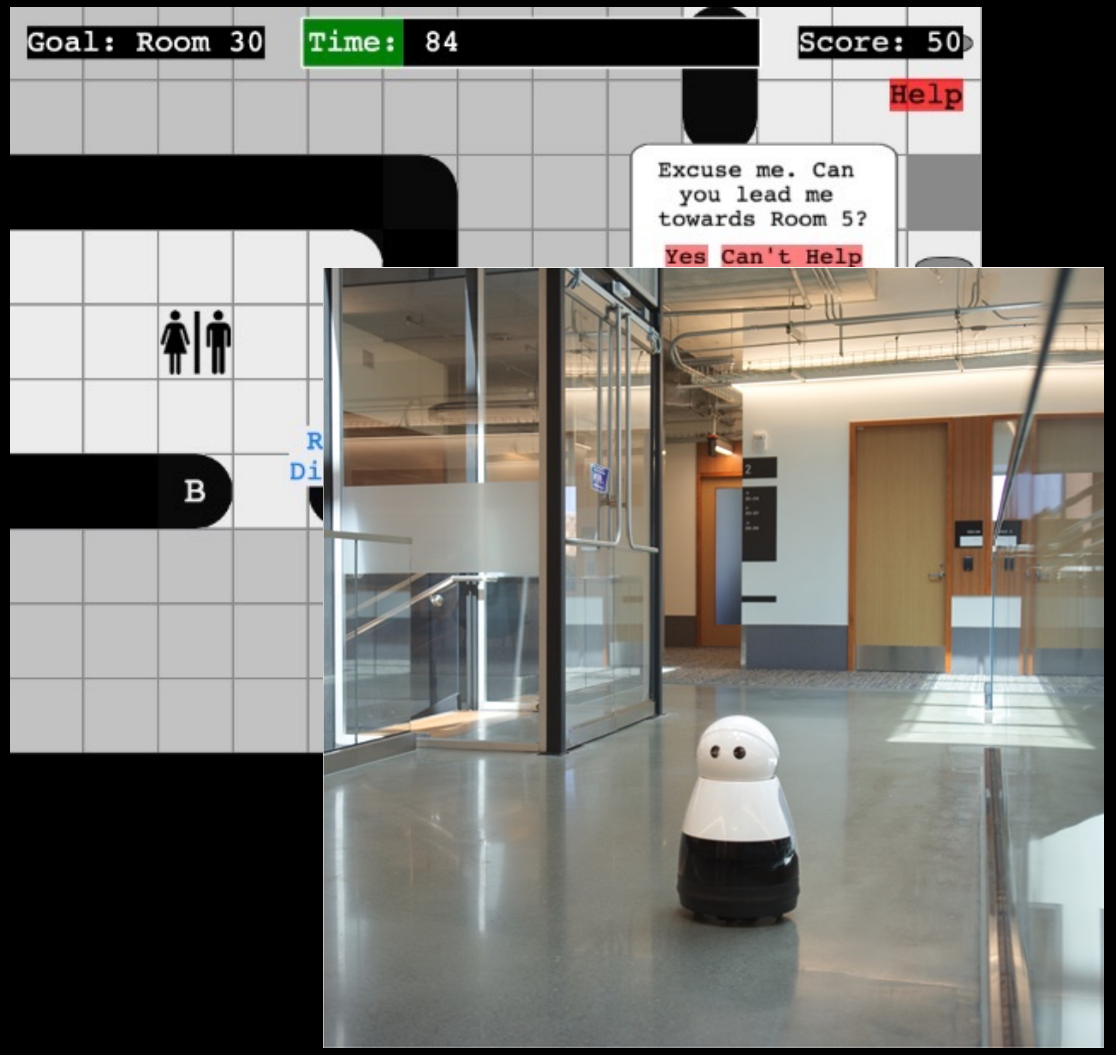
"[Contextual] was more annoying and asking (sic) for help than [Hybrid]."

Nanavati et al. RSS '21

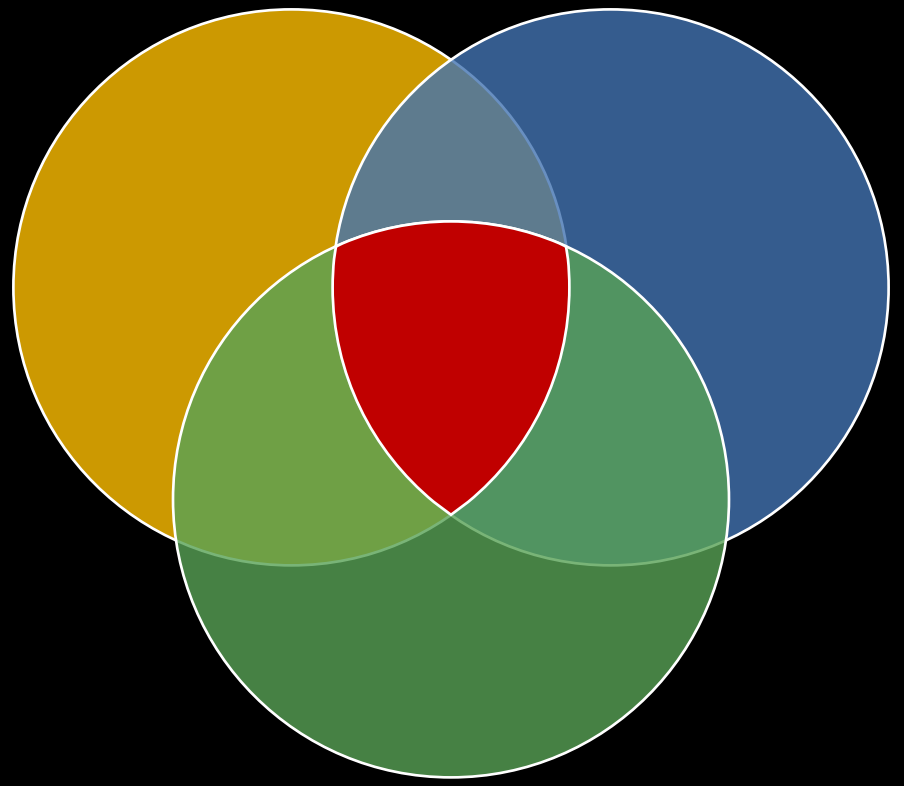
Towards long-term deployments

Multiagent domains

Learn recovery mechanisms from human feedback



This talk: a framework for social navigation



Takeaways

Domain insights empower simple prediction/control models

But scaling requires understanding human perceptions

Need for extensive user validation & benchmarks

Human help to scale performance & train users

Robots assisting humans in everyday life













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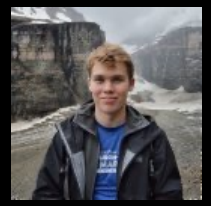

Kevin Weatherwax
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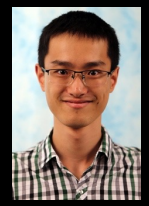

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Towards robots that navigate seamlessly next to people

Christoforos Mavrogiannis

Incoming Assistant Professor, Michigan Robotics

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