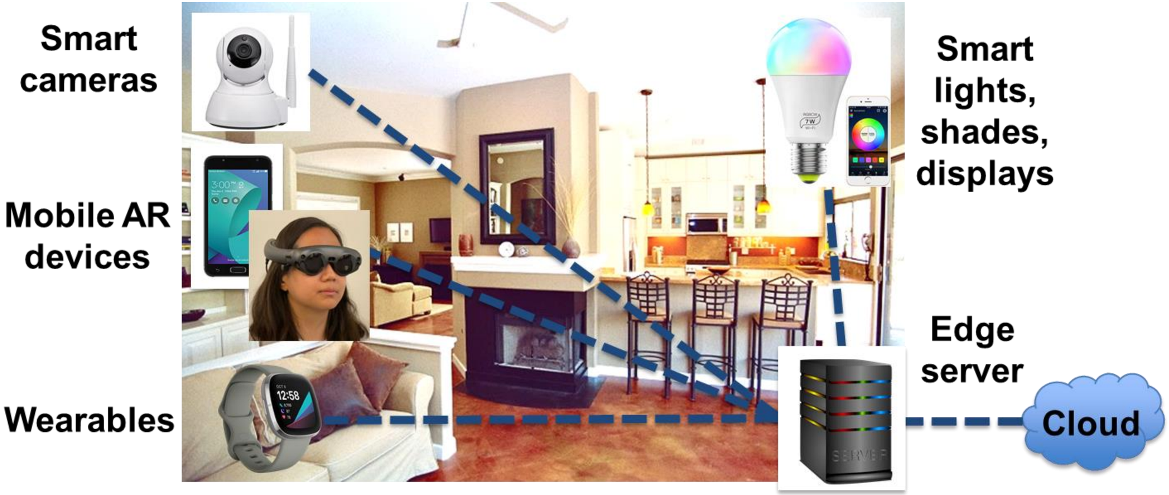
Intelligent Mobile Augmented Reality: Promise, Challenges, and Solutions



Maria Gorlatova

June 17, 2022

About the Speaker

- Nortel Networks Assistant Professor, ECE/CS, Duke University
- Previously:
  - Associate Research Scholar, Princeton University, Electrical Engineering
  - Ph.D. Columbia University, Electrical Engineering
  - Industry positions:

Telcordia Technologies

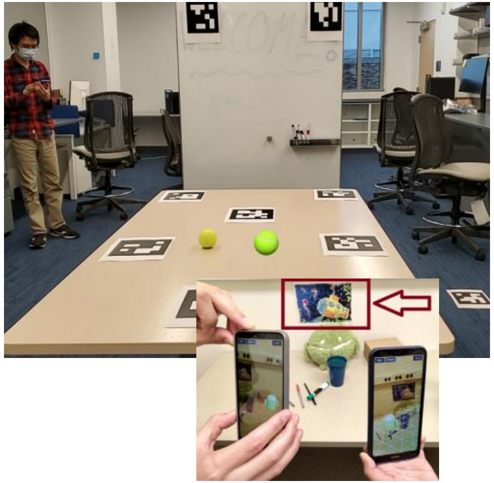
Disney Research

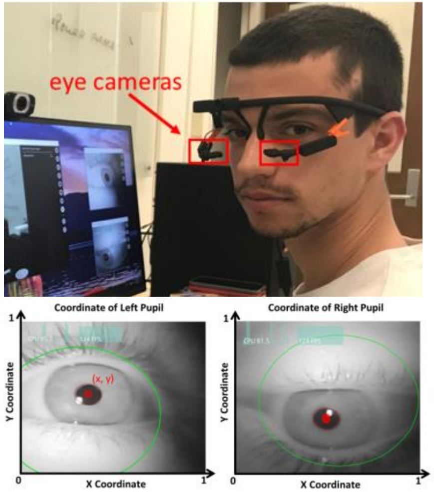
D E Shaw Research

IBM

Duke University Intelligent Interactive Internet of Things (I^3T) Lab

- Core research direction: **reliable context-aware** AR





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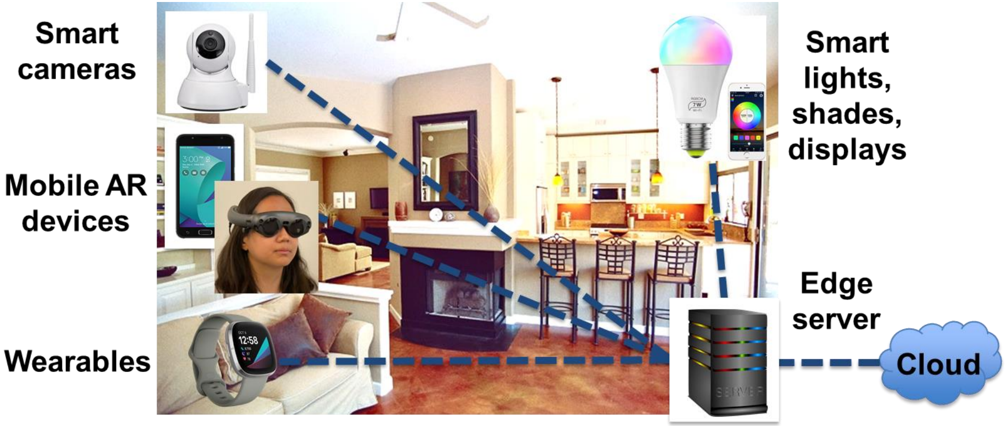
Outline

- **AR: current state and applications**
- Improving AR spatial and semantic awareness
- Improving user context awareness
- Summary and future work



Augmented Reality (AR): A Definition

- The [virtual] content is laid out around a user **in the same spatial coordinates as the physical objects surrounding her/him***

*From: Baldassi et al, Challenges and New Directions in Augmented Reality, Computer Security, and Neuroscience, June 2018.

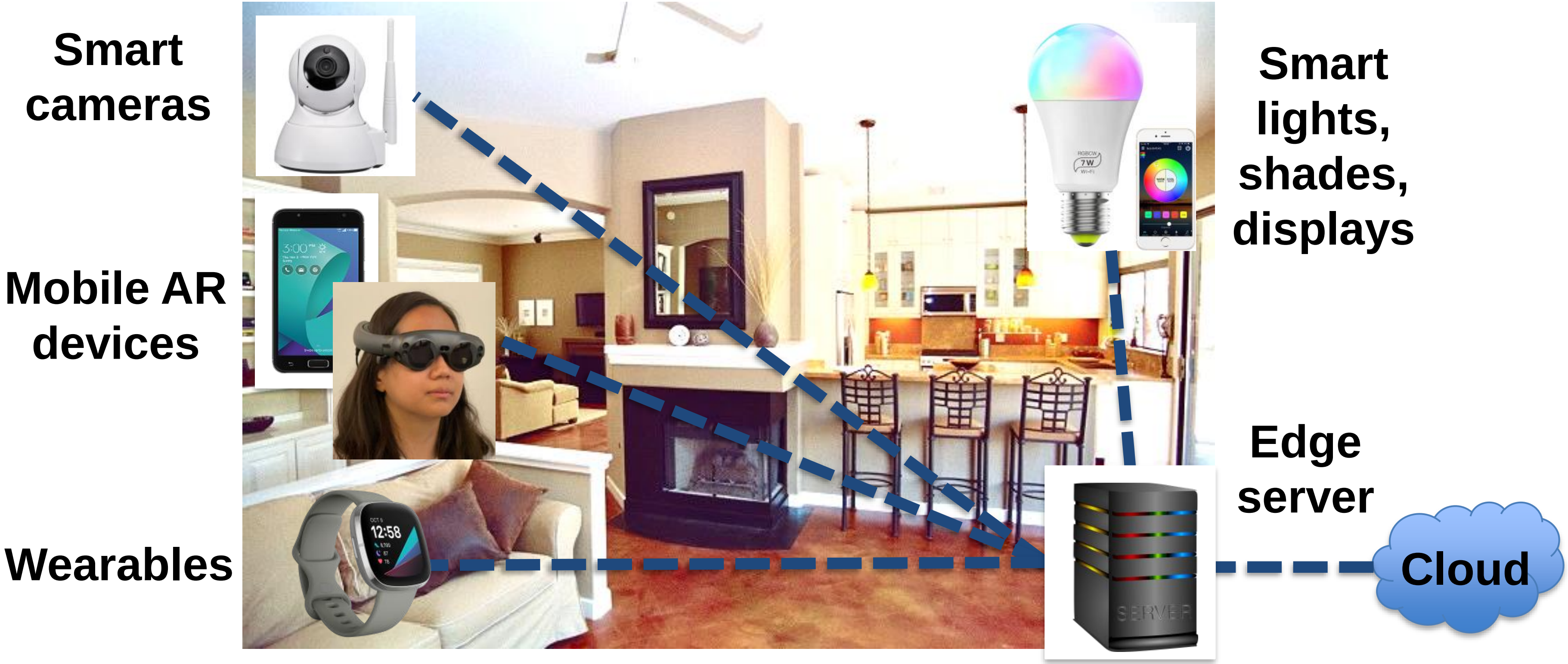
Modern AR: Multiple Device Options

- Google ARCore (2018), Apple ARKit (2017)
  - Vast majority of modern phone models support it
- Constantly expanding in devices and capabilities

Microsoft HoloLens (2016)

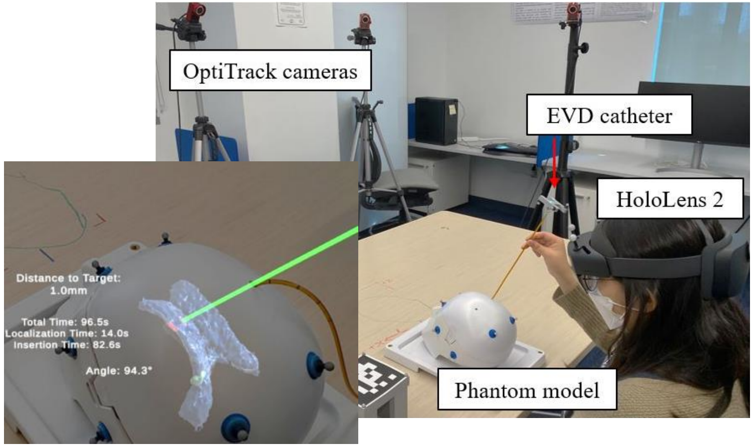
Magic Leap One (2018)

Our Vision: Multi-Device Mobile AR Architectures



Augmented Reality: Applications (1/2)

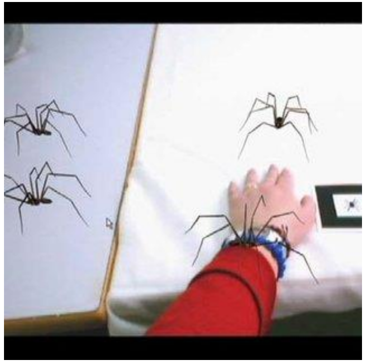
- **Seeing the invisible**
  - Navigation, education
  - AR-based **task guidance** has been demonstrated to out-perform paper-based and other guidance



- S. Eom, D. Sykes, S. Rahimpour, **M. Gorlatova**, under review. Work in progress version: AR-Assisted Surgical Guidance System for Ventriculostomy, in Proc. *IEEE XR for Healthcare and Wellbeing Workshop*, Mar. 2022 (co-located with *IEEE VR'22*).

Augmented Reality: Applications (2/2)

- **Influences users deeply and profoundly**
  - ➢ Studied in context of treating phobias
  - ➢ Interesting temperature perception studies
  - ➢ Several projects on AR for substance use disorders



❑ T. Scargill, Y. Chen, S. Eom, J. Dunn, **M. Gorlatova**, Environmental, User, and Social Context-Aware Augmented Reality for Supporting Personal Development and Change, in *Proc. IEEE Workshop for Building the Foundations of the Metaverse*, Mar. 2022 (co-located with *IEEE VR'22*).

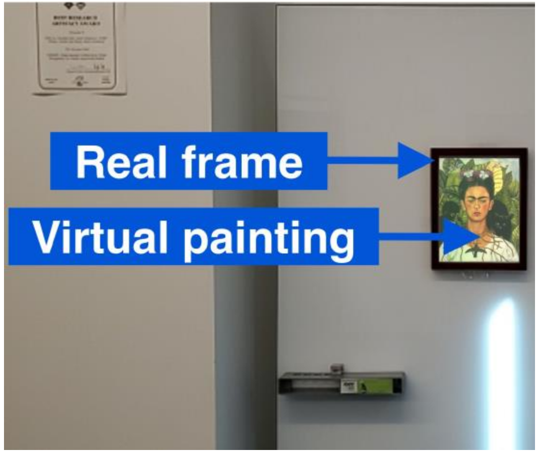
AR: Core Mobile Technology of the Future

"AR will redefine our relationship with technology"

"It is the next big thing, and will pervade our entire lives"

Mobile AR: Current State and Limitations

Already: impressive in **merging physical and digital worlds**



- Among key limitations: resource consumption, headset form factor, security and privacy
- **Context awareness**

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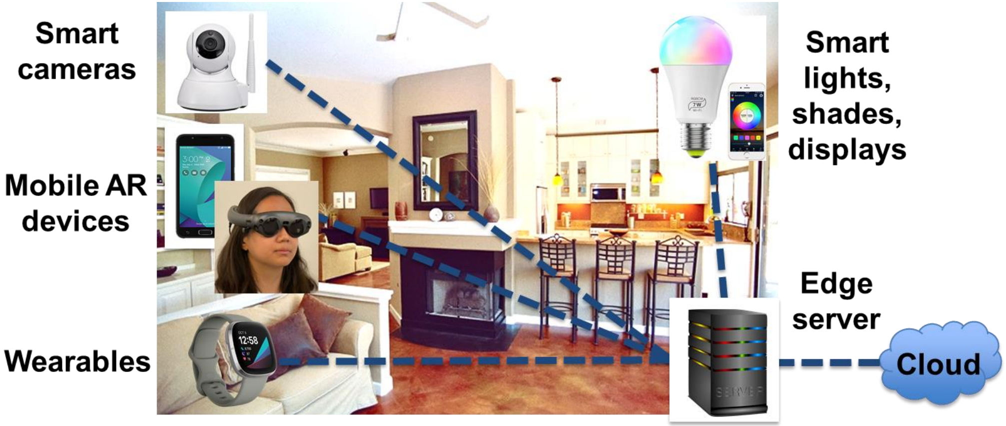
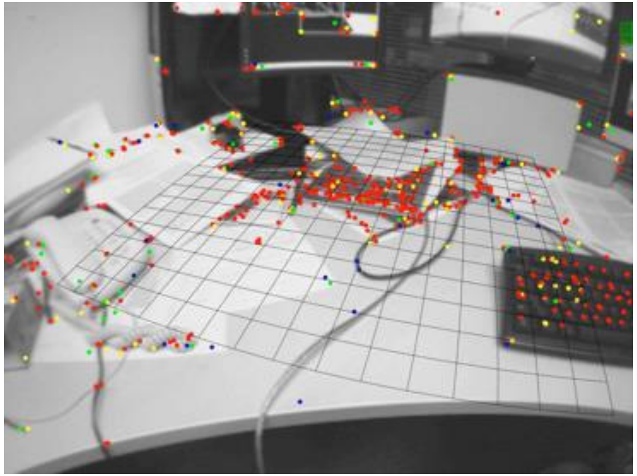
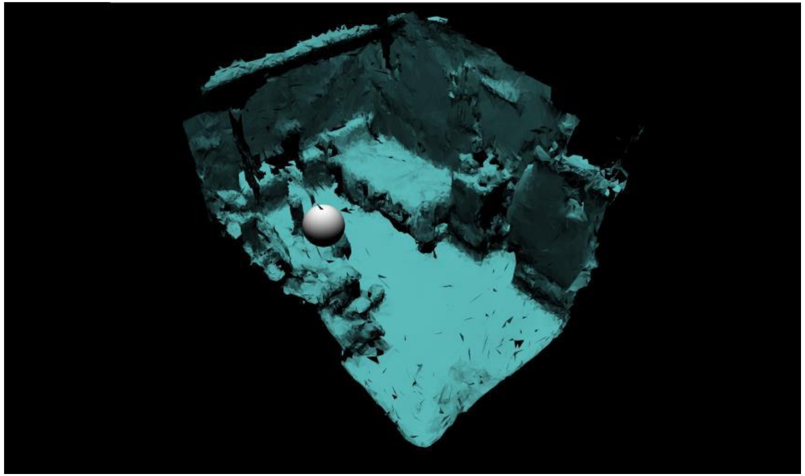


AR Spatial Awareness

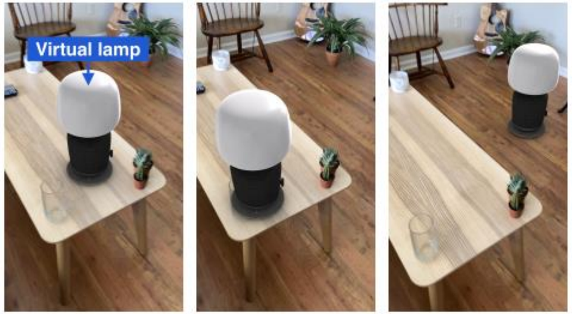
- Essential for integrating virtual objects with the real world
  - ➢ Sub-cm-level localization
- Without markers, achieved via **Visual-Inertial Simultaneous Localization and Mapping (VI-SLAM)**





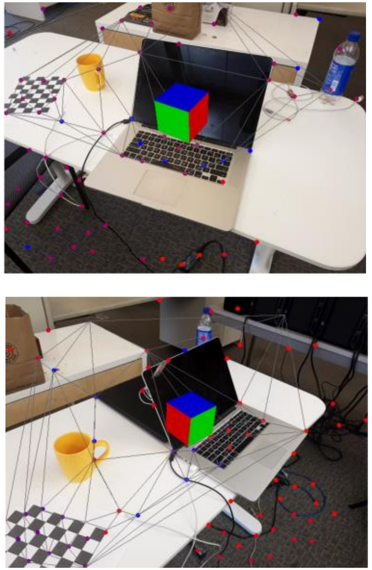
Errors in AR Spatial Awareness

- Virtual objects rendered in the wrong place



Unintended motion (*drift*)

Incorrect scale



Different locations for different users

- T. Scargill, G. Premsankar, J. Chen, **M. Gorlatova**, Here To Stay: A Quantitative Comparison of Virtual Object Stability in Markerless Mobile AR, in *Proc. IEEE/ACM CPHS Workshop*, 2022 (co-located with CPS-IoT Week).
- Y. Zhang, T. Scargill, A. Vaishnav, G. Premsankar, M. Di Francesco, **M. Gorlatova**, InDepth: Real-time Depth Inpainting for Mobile Augmented Reality, to appear in *Proc. ACM IMWUT*, 2022.
- X. Ran, C. Slocum, Y.-Z. Tsai, K. Apicharttrisorn, **M. Gorlatova**, J. Chen, Multi-User Augmented Reality with Communication Efficient and Spatially Consistent Virtual Objects, in *Proc. ACM CoNEXT*, Dec. 2020.

AR Semantic Awareness

- Understanding the nature of objects and surfaces in the space around the user
  - ➢ 2D and 3D object detection, segmentation, semantic mapping, …
- Will enable many important **context-aware** AR applications
  - ➢ Safety guidance, mobile health, diminished reality

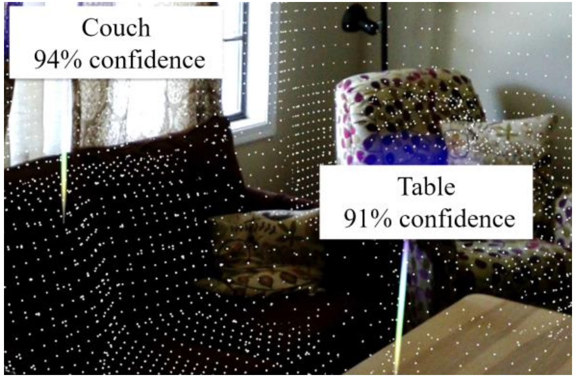
Avatar behavior adapted to conditions

Tahara et al, *IEEE ISMAR-adjunct'20*

Cars replaced with virtual objects

Kari et al, *IEEE ISMAR'21*

Semantic Awareness in AR: Challenges



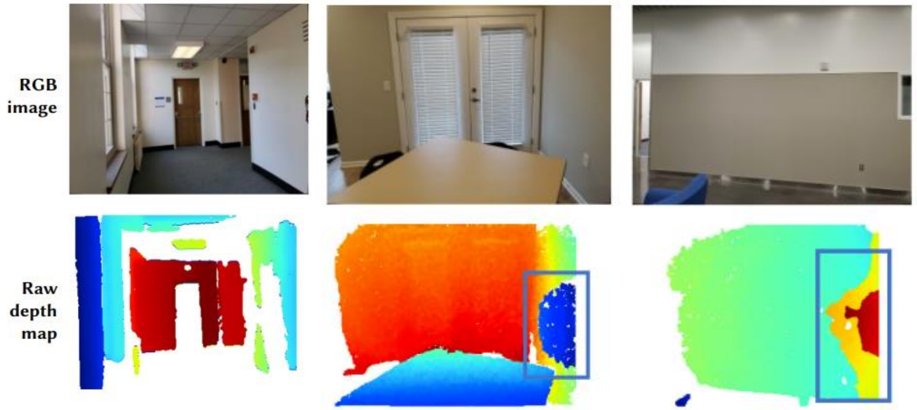
"*Even though object recognition rates can exceed 90% on many datasets, in the real world the results from these algorithms are* ***almost unusable***" – Huynh et al, *IEEE VR'19*

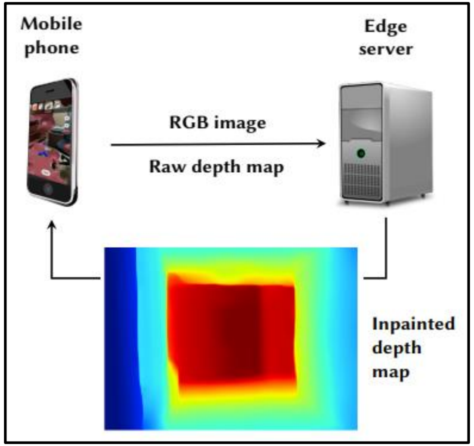
- Resource limitations, latency constraints
  - ➢ Edge computing: de-facto standard approach to solving these
- Multiple types of domain mismatches
  - ➢ Image quality, object pose, camera pose
- Open-set conditions

❑ Z. Liu, G. Lan, J. Stojkovic, Y. Zhang, C. Joe-Wong, **M. Gorlatova**, CollabAR: Edge-assisted Collaborative Image Recognition for Mobile Augmented Reality, in Proc. *IEEE/ACM IPSN*, Apr. 2020. **IEEE/ACM IPSN Best Research Artifact Award.**

Depth Inpainting for Improving Depth Perception

- Depth data artifacts lead to incorrect mapping of the space





- Solution:
  - ➢ New DNN and data augmentation for depth data *inpainting* and correction
  - ➢ Edge-based execution for meeting latency budgets

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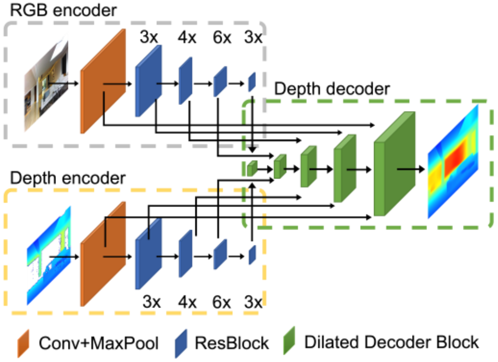
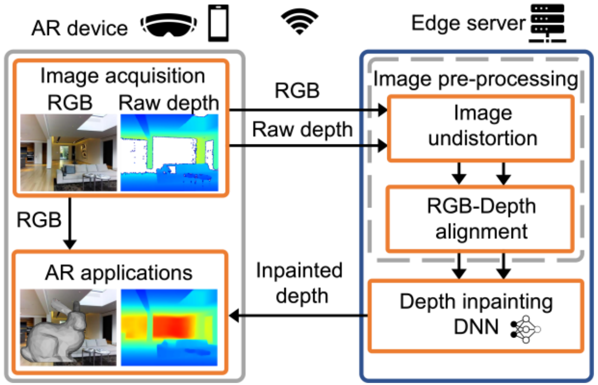
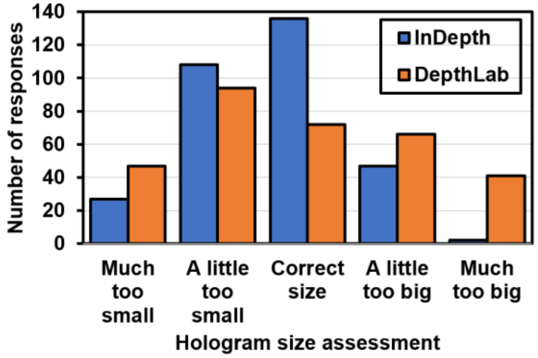


DNN architecture



System architecture



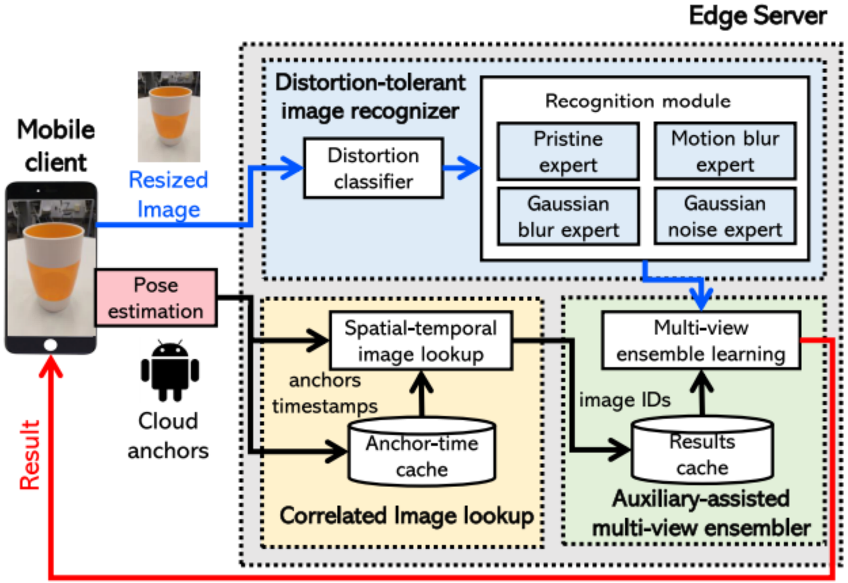
Depth error comparison

- InDepth outperforms state of the art while **reducing inference latency 10x**
- With edge support, achieves end to end latency **under 30 ms**
- Outperforms Google DepthLab on quantitative and qualitative metrics

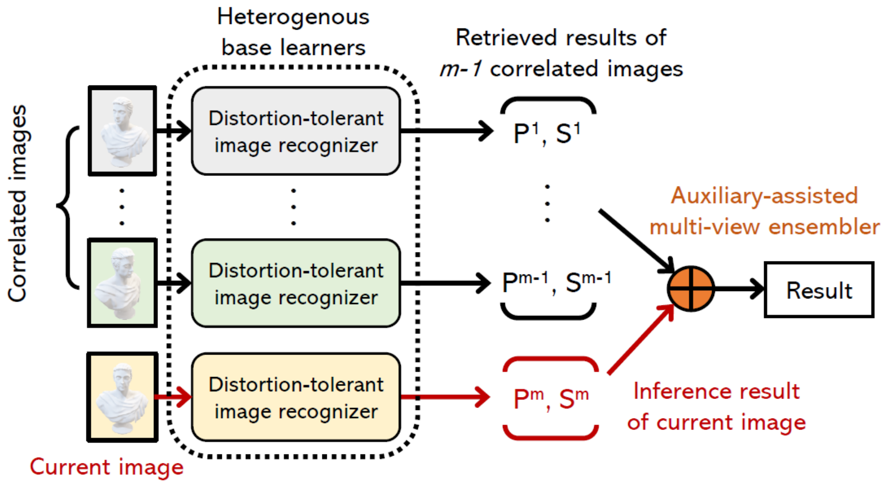
❑ Y. Zhang, T. Scargill, A. Vaishnav, G. Premsankar, M. Di Francesco, **M. Gorlatova**, InDepth: Real-time Depth Inpainting for Mobile Augmented Reality, to appear in *Proc. ACM IMWUT*, 2022.

Multiple Views of the Same Scene to Improve Semantic Awareness

- DNN-based image recognition enables seamless contextual AR
- Challenge: DNNs make mistakes
  - ➢ Distortions, non-standard object poses, occlusions
- Multiple views of a scene can help



CollabAR: Collaborative Image Recognition for AR



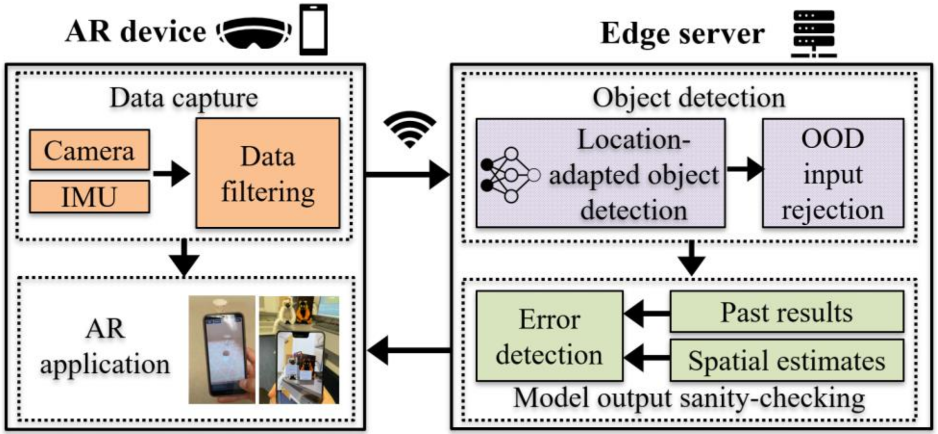
Auxiliary-assisted Multiview Ensemble Learning

- Improves recognition accuracy by 16% to 20% in severe distortions scenario

	Nokia 7.1	Pixel 2 XL
On-device	67.2 ms	34.7 ms
Edge	19.9 ms	19.8 ms

- G. Lan, Z. Liu, Y. Zhang, T. Scargill, J. Stojkovic, C. Joe-Wong, **M. Gorlatova**, Edge-assisted Collaborative Image Recognition for Mobile Augmented Reality, *ACM Transactions on Sensor Networks*, Vol. 18, No 1, Feb. 2022.
- Z. Liu, G. Lan, J. Stojkovic, Y. Zhang, C. Joe-Wong, **M. Gorlatova**, CollabAR: Edge-assisted Collaborative Image Recognition for Mobile Augmented Reality, in Proc. *IEEE/ACM IPSN*, Apr. 2020. **IEEE/ACM IPSN Best Research Artifact Award.**

Ongoing Work: Robust AR Object Detection



- Application: AR enhancing experience of Duke Lemur Center visitors
  - ➢ Traditional object detectors' results are ≈ random guess

❑ Students Code Alternate Realities, Pratt School of Engineering, Aug. 2020, https://pratt.duke.edu/about/news/students-code-alternate-realities

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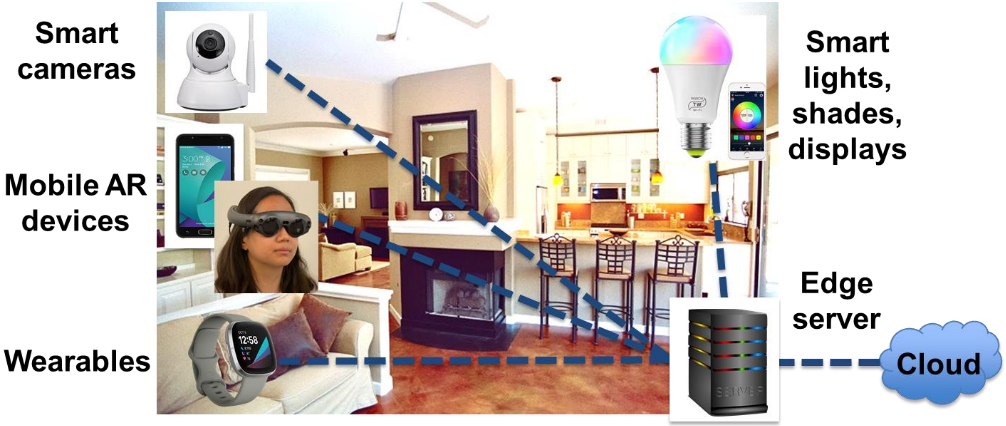
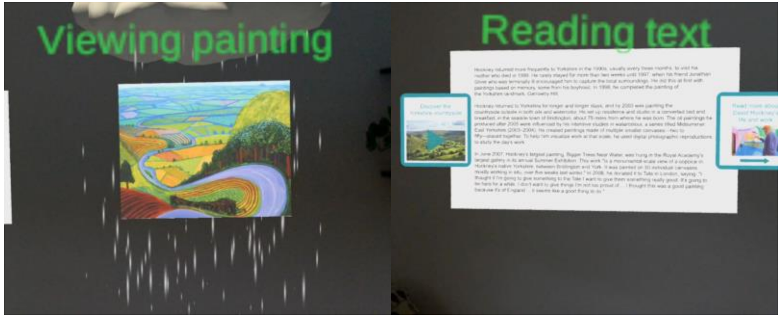


AR User Context Awareness

- User context awareness:
  - ➢ Understanding what the user is doing and how the user is feeling
  - ➢ Automatically assessing user’s level of expertise, concentration, mental and physical fatigue
- AR: immersive experiences tailored to the state of the user



❑ T. Scargill, G. Lan, **M. Gorlatova**, Demo: Catch My Eye: Gaze-Based Activity Recognition in an Augmented Reality Art Gallery, in *Proc. ACM/IEEE IPSN*, May 2022.

User Context Awareness: Opportunities and Challenges

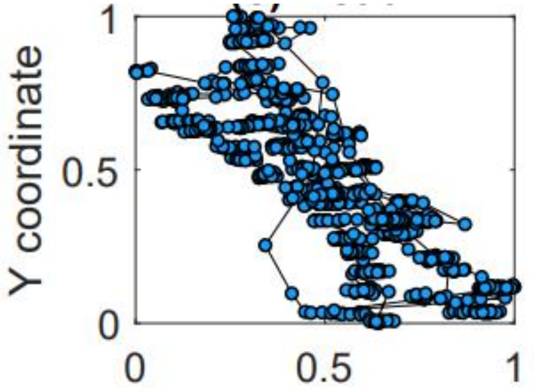
- Intimately connected with the user
  - AR **sees what you see and hears what you hear**
  - Eye tracking: looks deep inside your soul
- Wearables add new opportunities

- Challenges: training **personalized** algorithms
  - Population-level models do not work well on individual users
  - Can't collect too much data → Fine-tuning and few-shot learning
  - Personal data can be highly sensitive → Edge computing for enhanced privacy controls

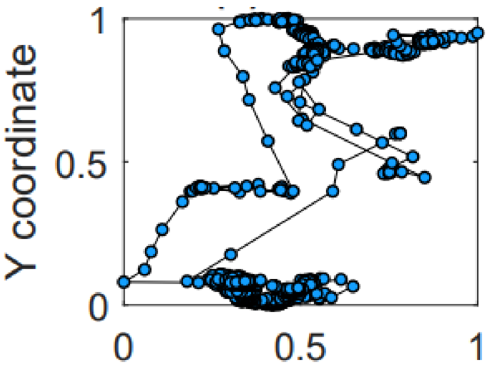
❑ Y. Jiang, W. Wang, T. Scargill, M. Rothman, **M. Gorlatova**, J. Dunn, Digital biomarkers reflect stress reduction after Augmented Reality guided meditation: a feasibility study, in *Proc. ACM Workshop on Emerging Devices for Digital Biomarkers*, May 2022 (co-located with ACM MobiSys 2022).

Eye Tracking-based Cognitive Context Sensing

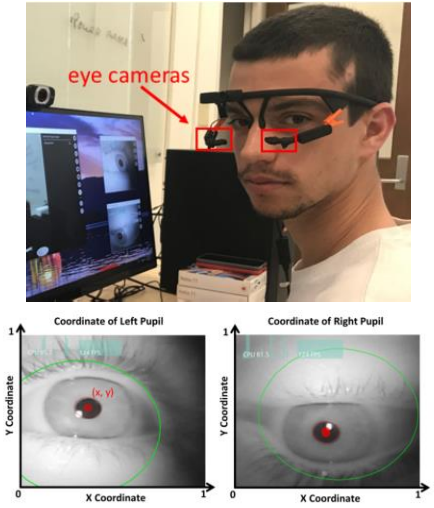
- Important part of AR and VR hardware
- Powerful source of information about the user
  - ➢ Both ***where*** and ***how*** the user looks



Reading text

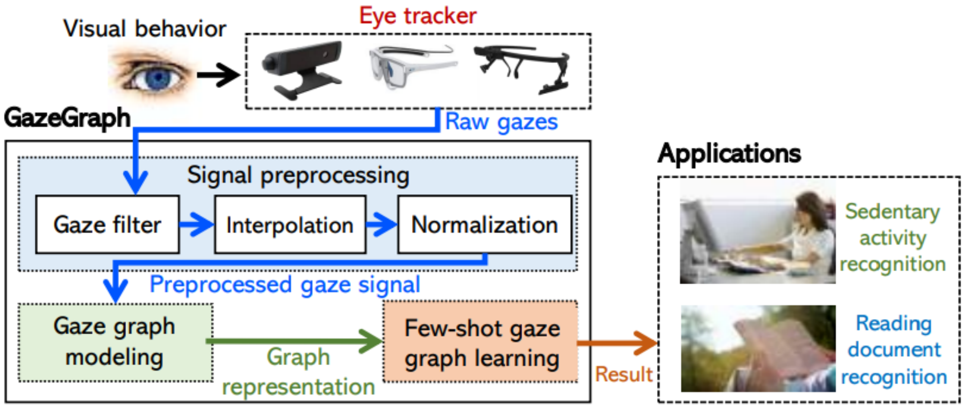


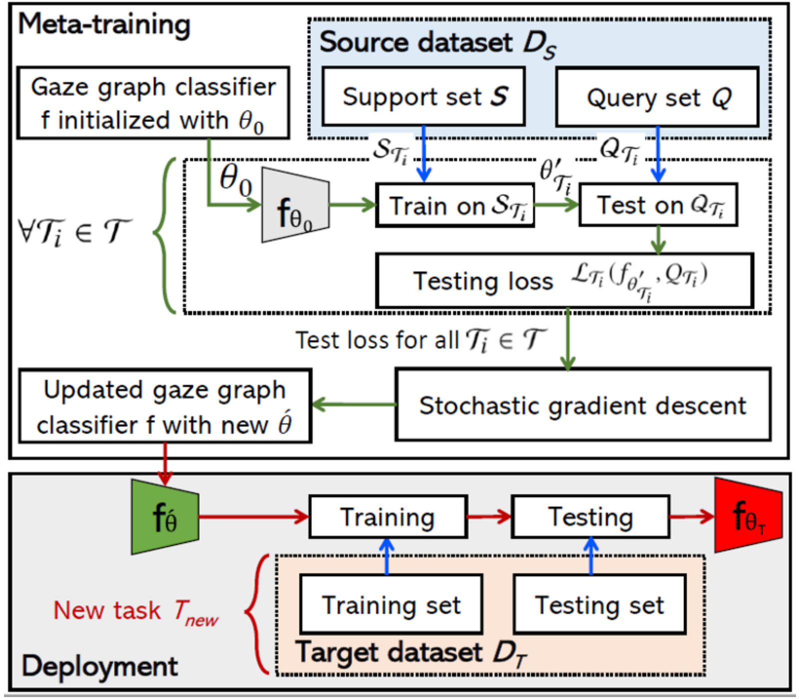
Watching a movie with subtitles



Eye Tracking-based Cognitive Context Sensing

- Challenges:
  - Highly heterogenous across subjects, stimuli, eye tracking devices
  - Need to work in few-shot conditions

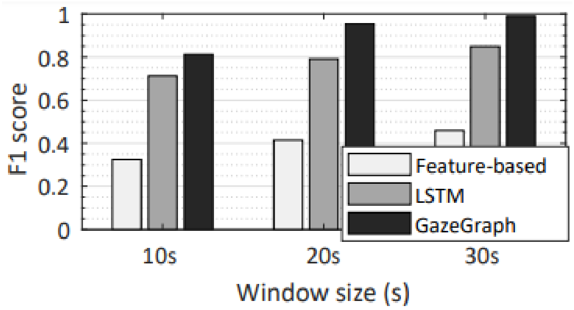


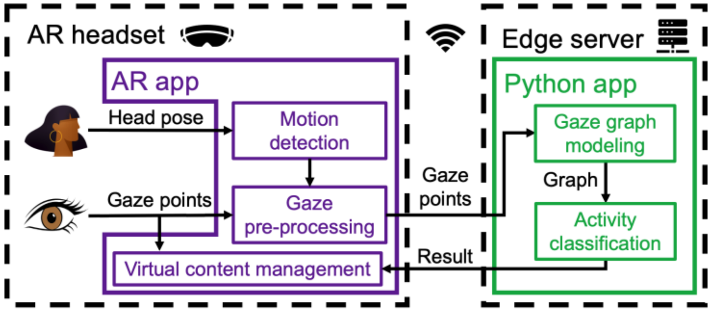


❑ G. Lan, B. Heit, T. Scargill, **M. Gorlatova**, GazeGraph: Graph-based Few-Shot Cognitive Context Sensing from Human Visual Behavior, in *Proc. ACM SenSys*, Nov. 2020.

Cognitive Context Detection with GazeGraph

- Outperforms feature-based methods by 37-54%, LSTM-based methods by 10-23%
- Outperforms transfer learning-based approaches by 19-30%





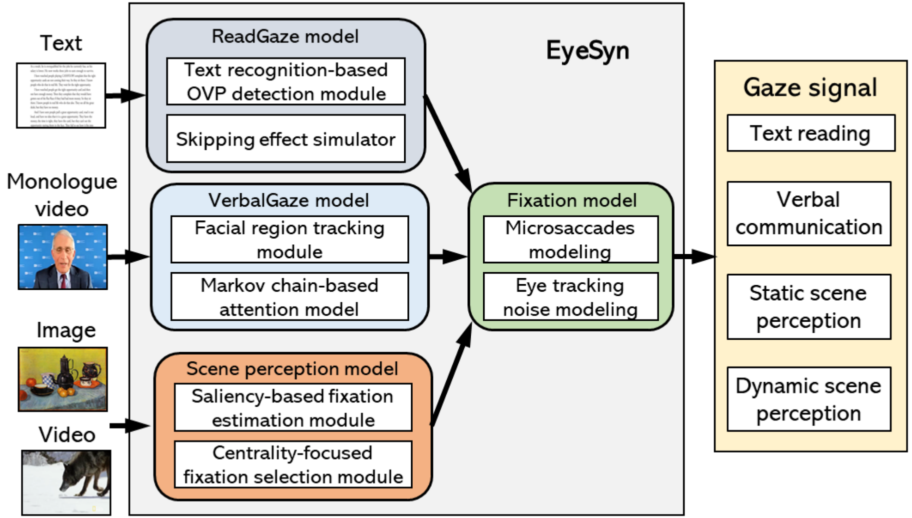
- Pre-processing, graph construction, and DNN inference time: under 15 ms
- Overall latency: under 100 ms
- Demonstrated *first gaze-based activity recognition in an AR app*

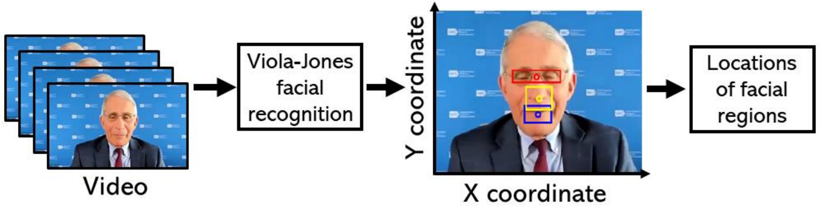
❑ T. Scargill, G. Lan, **M. Gorlatova**, Demo: Catch My Eye: Gaze-Based Activity Recognition in an Augmented Reality Art Gallery, in *Proc. ACM/IEEE IPSN*, May 2022.

❑ G. Lan, B. Heit, T. Scargill, **M. Gorlatova**, GazeGraph: Graph-based Few-Shot Cognitive Context Sensing from Human Visual Behavior, in *Proc. ACM SenSys*, Nov. 2020.

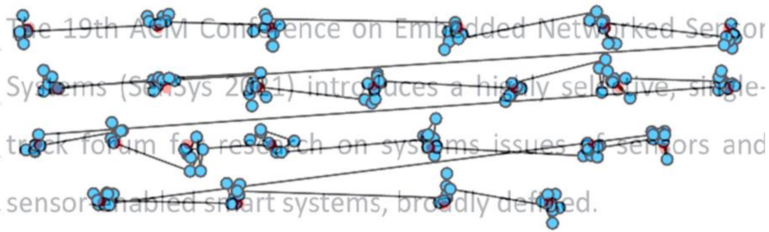
Eye Movement Synthesis for Context Detection

- Psychology-inspired generative models for *synthesizing* arbitrarily large realistic eye movement datasets





Human visual attention in a conversation

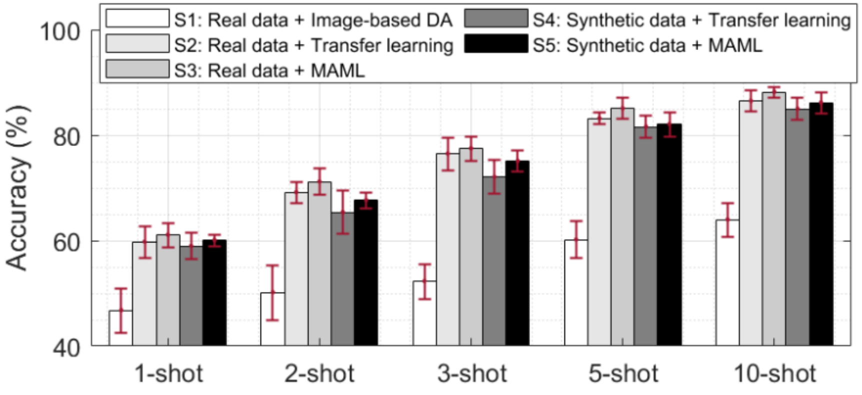


Human visual attention when reading

- G. Lan, T. Scargill, **M. Gorlatova**, EyeSyn: Psychology-inspired Eye Movement Synthesis for Gaze-based Activity Recognition, in *Proc. IEEE/ACM IPSN*, May 2022. **Selected media coverage: vice.com, hackster.io. Highlighted in the university-wide Duke Daily and in the NSF-wide Discoveries newsletters.**

Eye Movement Synthesis: Gaze-based Activity Recognition Case Study

Activity	Simulation inputs	Simulated data length
Read	300 text images from three books	9.9 hours
Communicate	100 video clips of monologue interview	30.9 hours
Browse	7,937 images of paintings	132.3 hours
Watch	50 video clips of documentary videos	11.7 hours

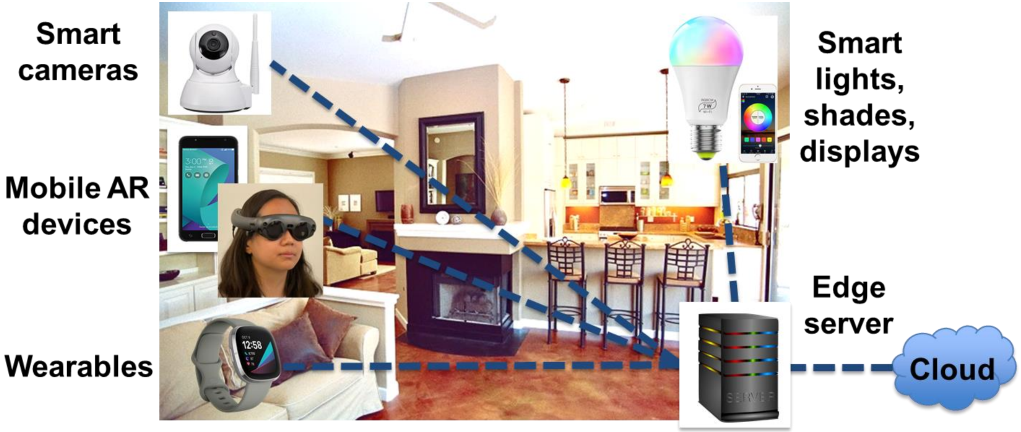


- Small accuracy drop (0.8-4.2%) compared to training on collected human data

❑ G. Lan, T. Scargill, **M. Gorlatova**, EyeSyn: Psychology-inspired Eye Movement Synthesis for Gaze-based Activity Recognition, in *Proc. IEEE/ACM IPSN*, May 2022. Code & data available via GitHub at https://github.com/EyeSyn/EyeSynResource. **Selected media coverage: vice.com, hackster.io. Highlighted in the university-wide Duke Daily and in the NSF-wide Discoveries newsletters**

Summary and Future Work

- **Spatial**, **semantic**, and **user** context awareness
- **Edge computing**: key enabler of advanced capabilities
- Future work: wearables and the IoT: additional sources of information



- Need privacy-aware solutions
  - ➢ But cannot compromise on performance

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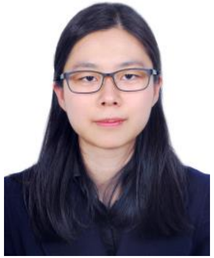







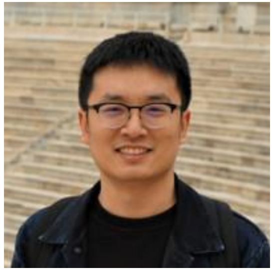




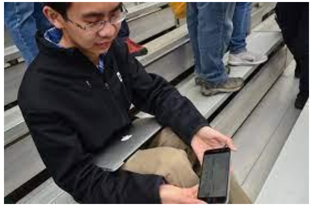

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Selected Publications

- Y. Zhang, T. Scargill, A. Vaishnav, G. Premsankar, M. Di Francesco, **M. Gorlatova**, InDepth: Real-time Depth Inpainting for Mobile Augmented Reality, to appear in *Proc. ACM IMWUT*, 2022.
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Questions?

- E-mail the speaker: maria.gorlatova@duke.edu