Creating the Virtual Reality of the Future with Artificial Intelligence and Computational Design

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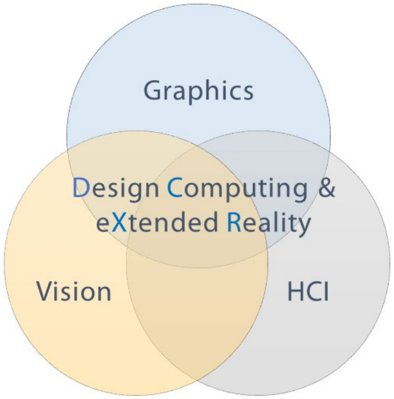
Design Computing and eXtended Reality

What will the future of work, entertainment, and everyday life be 5-10 years from now?

Interests: Computer Graphics, Computer Vision, HCI

Techniques: Optimization, Artificial Intelligence, Machine Learning, Simulation

Applications: VR/AR, Computational Design, User Interfaces

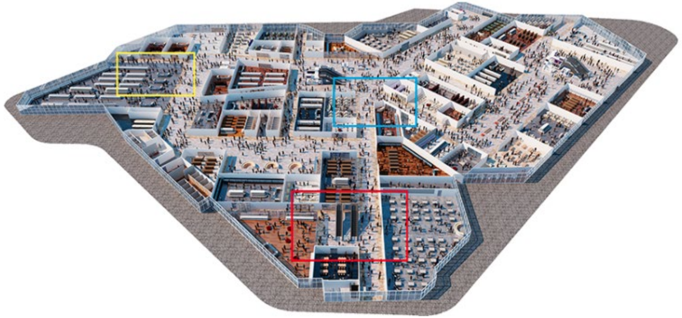


AI for Design (e.g., interior design, architectural design, product design)

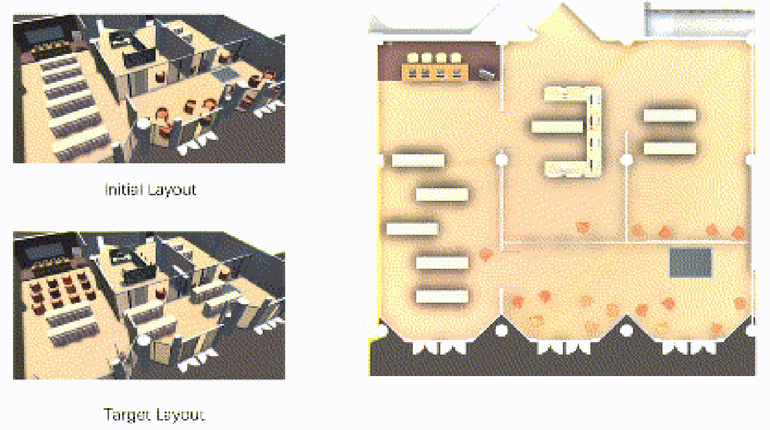
[SIGGRAPH 2015]

[SIGGRAPH Asia 2016]

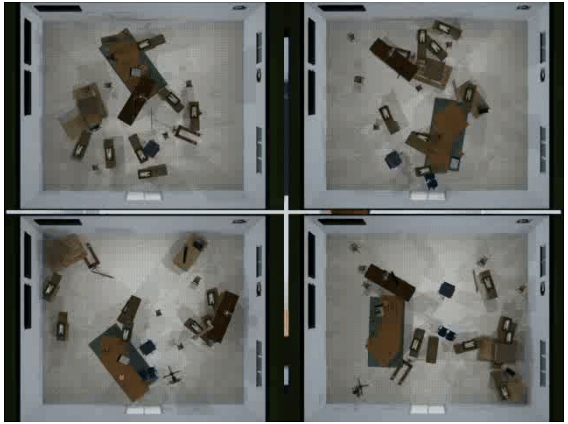
[SIGGRAPH 2016]



[SIGGRAPH Asia 2020]

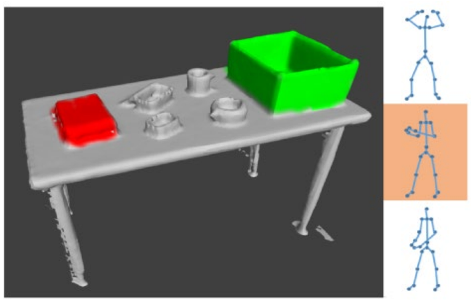


[SIGGRAPH 2011]

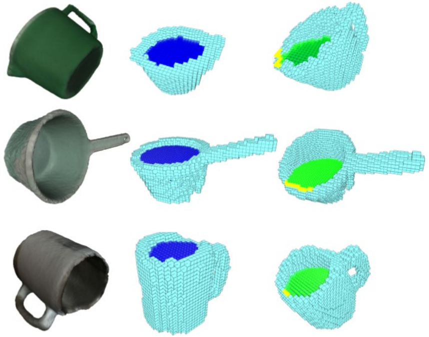


Scene Understanding and Reconstruction (e.g., stereo, affordance analysis)

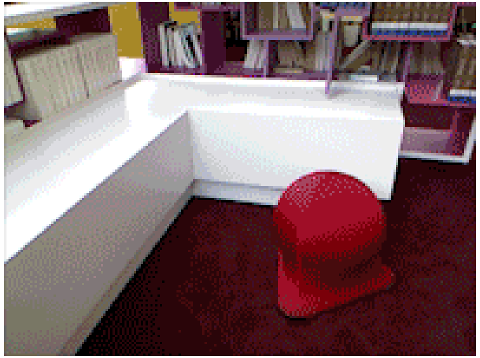
[ICCV 2017]



[ICCV 2015]

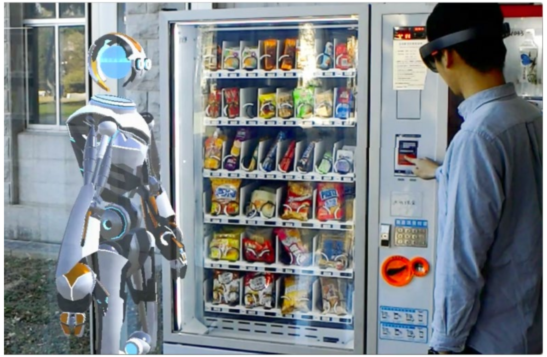


[CVPR 2013]



[3DV 2016]

[VR 2019]



[CHI 2021]

Virtual Reality Adaptive Training (e.g., driving, disaster response, exergaming, education)

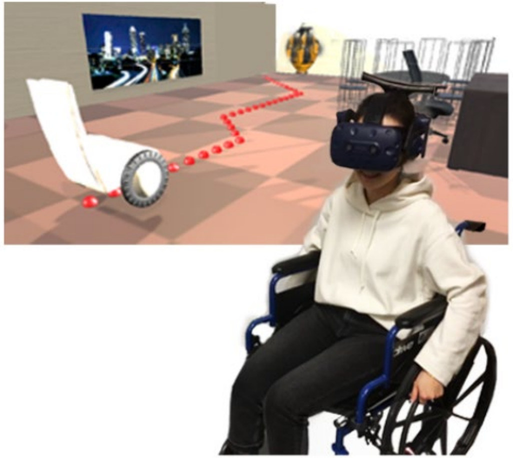
[VR 2018]

[VR 2018]

[VR 2017]

[SIGGRAPH 2020]

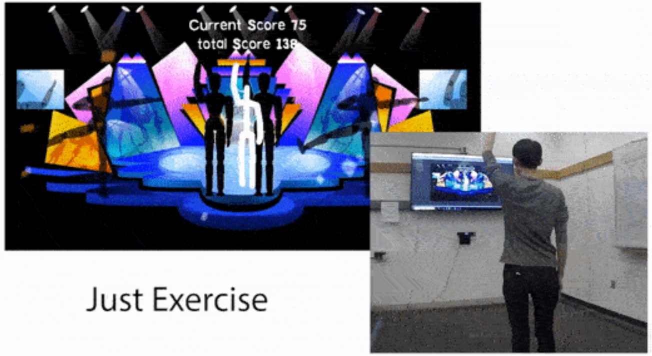
[VR 2020]



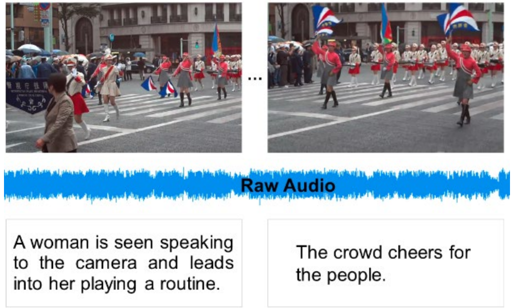
Computational Interaction (e.g., novel wayfinding tool, virtual experiences, synthesized sound/speech)

[CHI 2019]

[CHI 2019]



[CHI 2021]



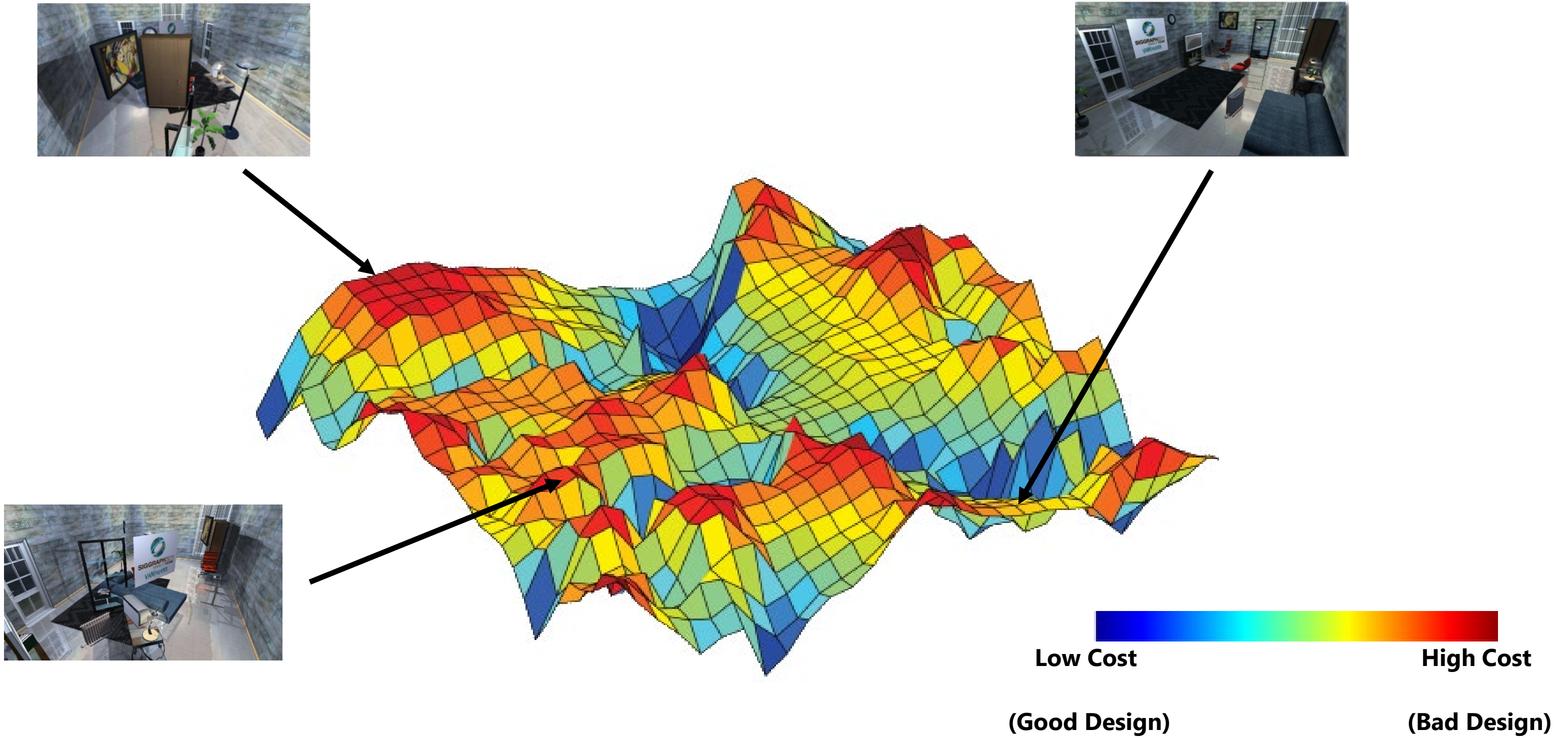
[CHI 2019]

[SIGGRAPH Asia 2019]

Computational Design

Computational Design Framework

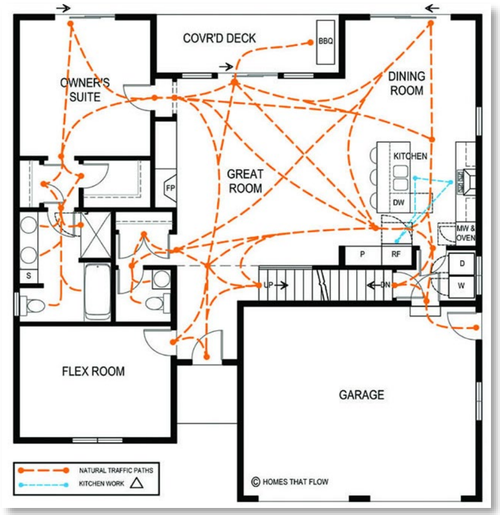
Design Solution Space

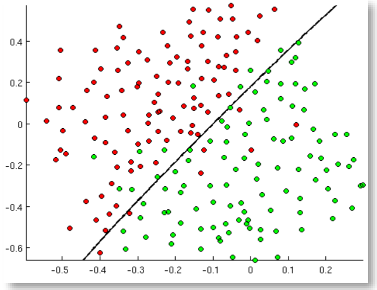


Computational Design Framework

Design Goals

- Functionality (e.g., ergonomics, physical properties)
- Aesthetics prior (e.g., color, style)





Computational Design Framework

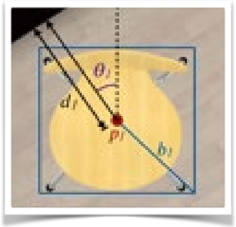
Design Constraints

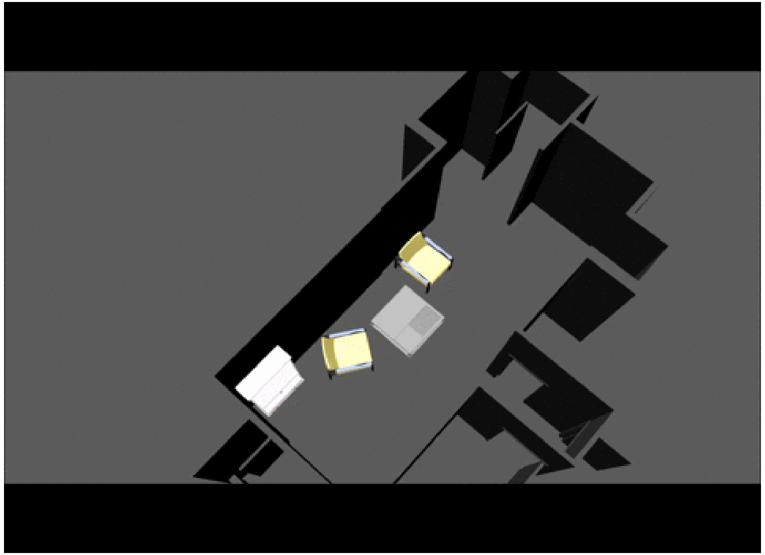
- Space
- Budget (e.g., cost, material, time, labor)

Computational Design Framework

Design Variables

- Positions of objects

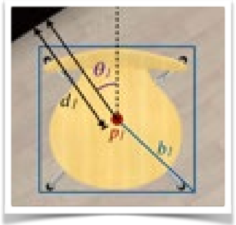


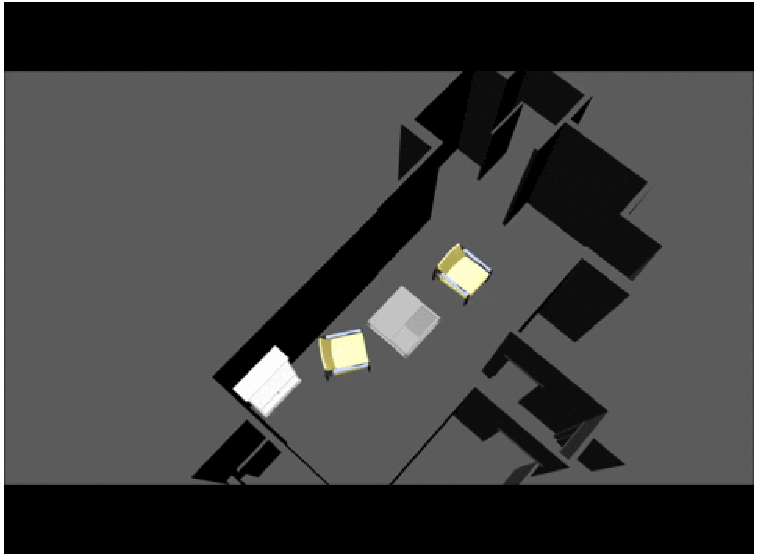


Computational Design Framework

Design Variables

- Orientations of objects

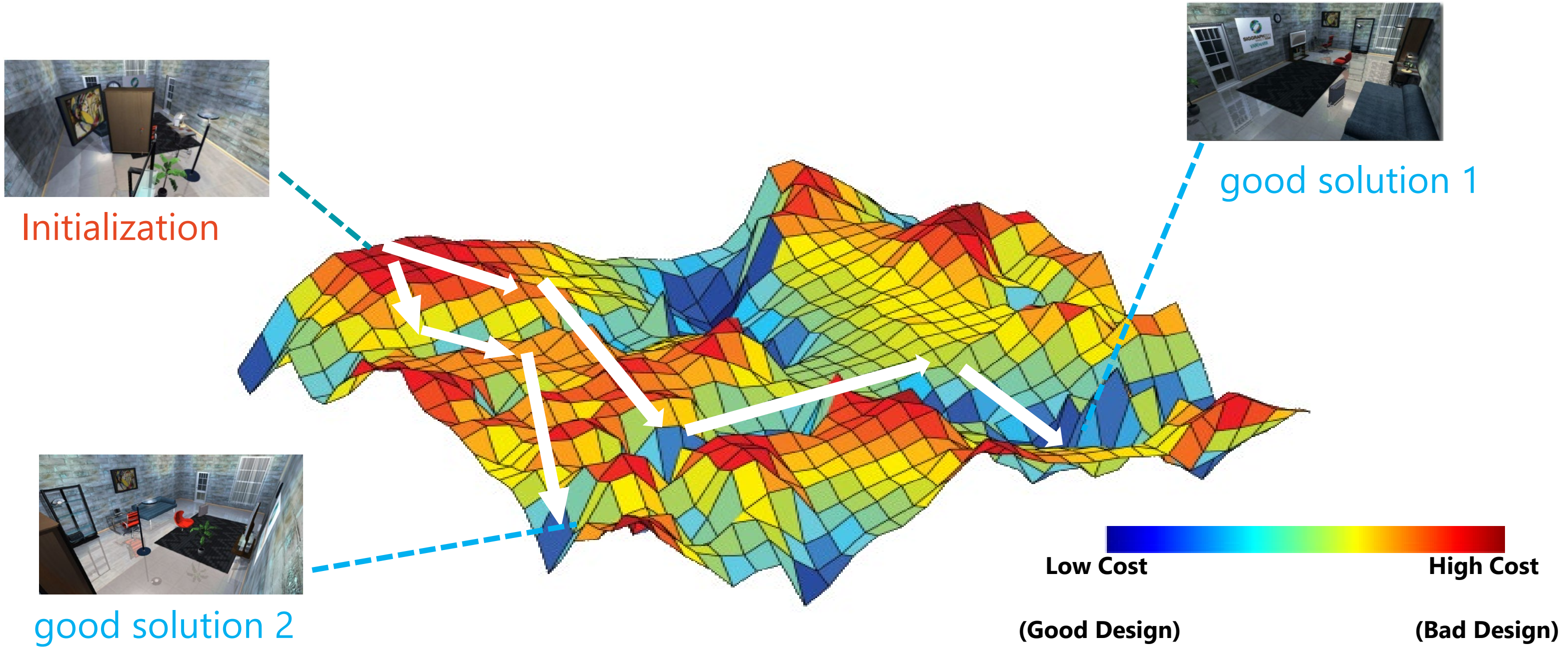




Computational Design Framework

Search for Solutions

- Optimization
- Statistical Inference (e.g., MCMC)

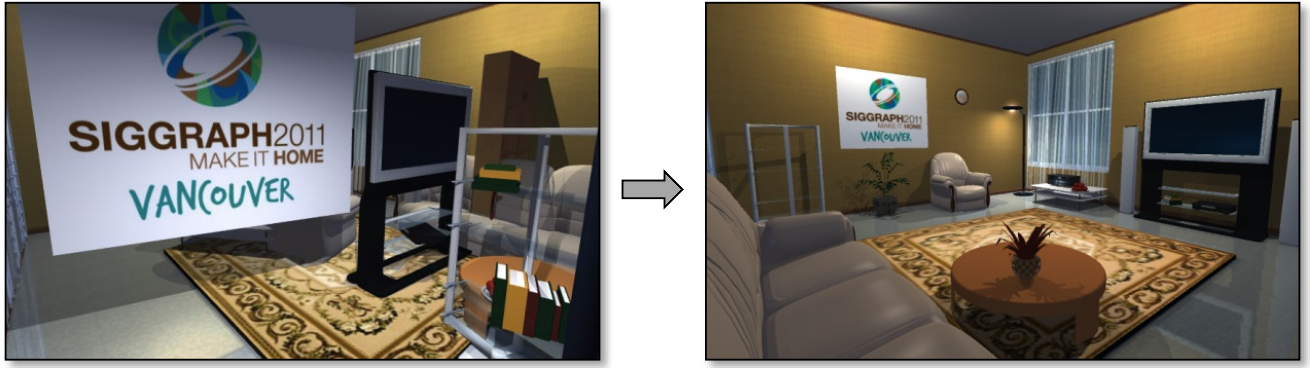


Virtual Environment Synthesis

Virtual Environment Synthesis

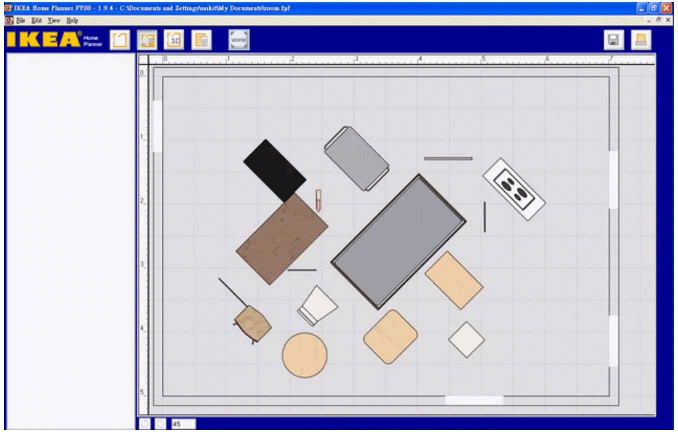
“Make it Home: Automatic Optimization of Furniture Arrangement”, *SIGGRAPH 2011*
Lap-Fai Yu, Sai-Kit Yeung, Chi-Keung Tang, Demetri Terzopoulos, Tony F. Chan, Stanley J. Osher

MAKE IT HOME
SIGGRAPH2011
VANCOUVER



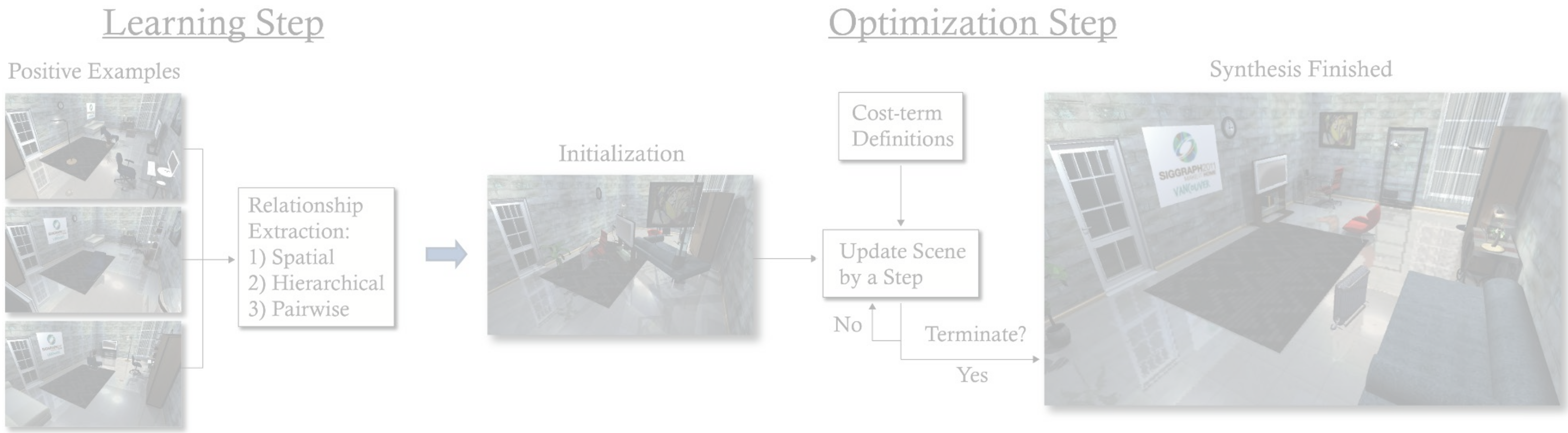
Design Acceleration

Traditional (CAD):



Our Method (Computational Design):

Our Approach



Optimization: Total Cost Function

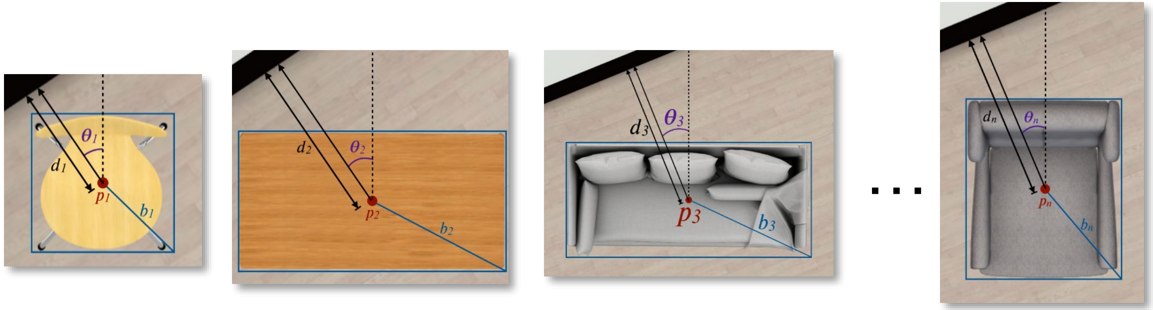
$$
\begin{aligned}
C(\phi) = {} & w_{\mathrm{a}} C_{\mathrm{a}}(\phi) + w_{\mathrm{v}} C_{\mathrm{v}}(\phi) + w_{\mathrm{path}} C_{\mathrm{path}}(\phi) \\
& + w_{\mathrm{pr}}^{d} C_{\mathrm{pr}}^{d}(\phi) + w_{\mathrm{pr}}^{\theta} C_{\mathrm{pr}}^{\theta}(\phi) \\
& + w_{\mathrm{pair}}^{d} C_{\mathrm{pair}}^{d}(\phi) + w_{\mathrm{pair}}^{\theta} C_{\mathrm{pair}}^{\theta}(\phi)
\end{aligned}
$$

Ergonomics

Prior

$$\phi = \{(p_i, \theta_i) | i = 1 \ldots n\}$$

Position, Orientation



Optimization

Simulated Annealing

- Computational imitation of physical annealing process

Cooling schedule:

- At the beginning, high temperature:

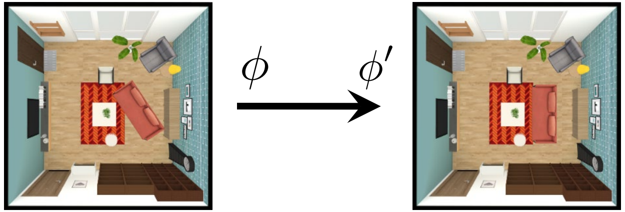
  → "heat up" furniture objects, allow flexible rearrangement
- Over time, temperature lowers gradually:

  → rearrangement is less aggressive
- At the end, temperature drops to zero:

  → refine final arrangement

Optimization

- At each iteration, a “move” is proposed,
  - Moves: translation, rotation, swapping objects, moving pathway controls
  - Transition:



  - Metropolis criterion determines transition probability:

$$\alpha(\phi' | \phi) = \min\left[\frac{f(\phi')}{f(\phi)}, 1\right]$$

$$= \min\left[\exp(\beta(C(\phi) - C(\phi'))), 1\right]$$

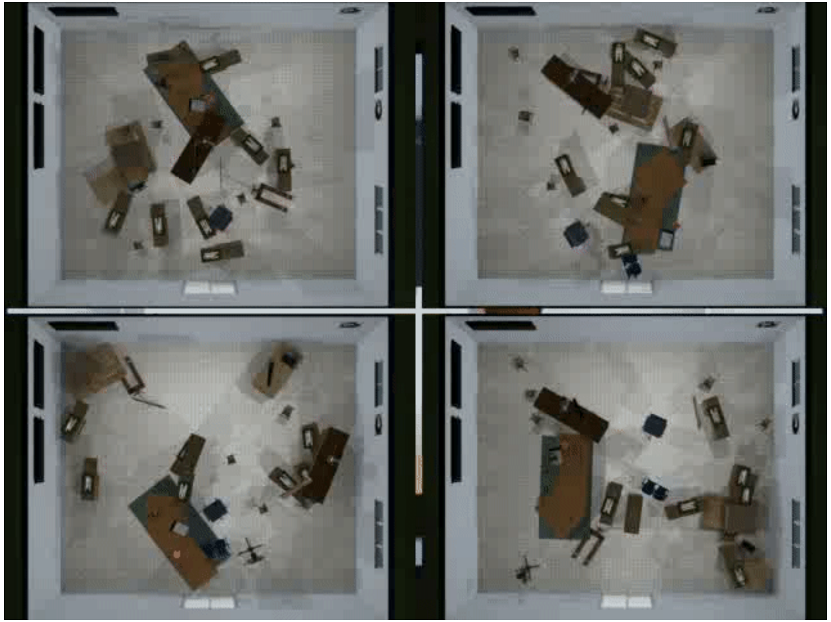
,where $$f(\phi) = e^{-\beta C(\phi)}$$

$$\beta \propto \frac{1}{Temperature}$$

C decreases, $\alpha = 1$

C increases, $0 < \alpha < 1$

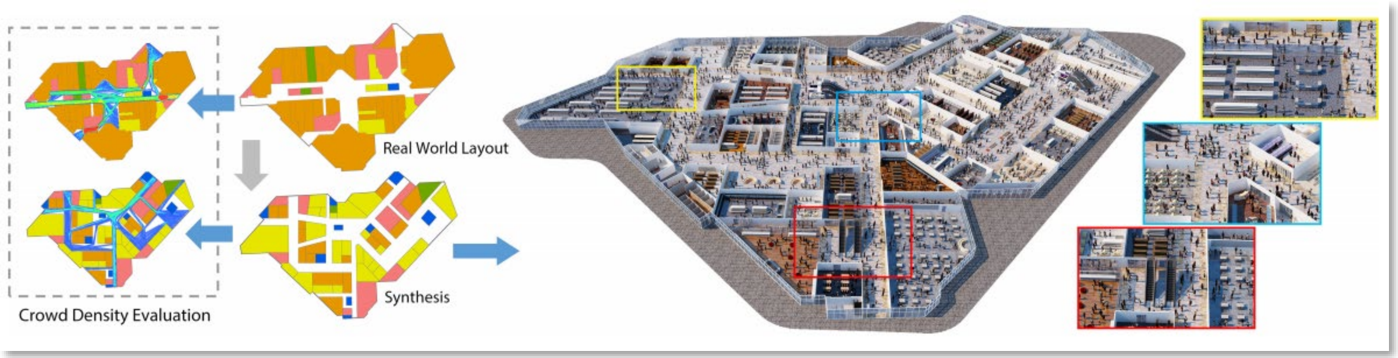
Design Exploration



3D Walkthrough

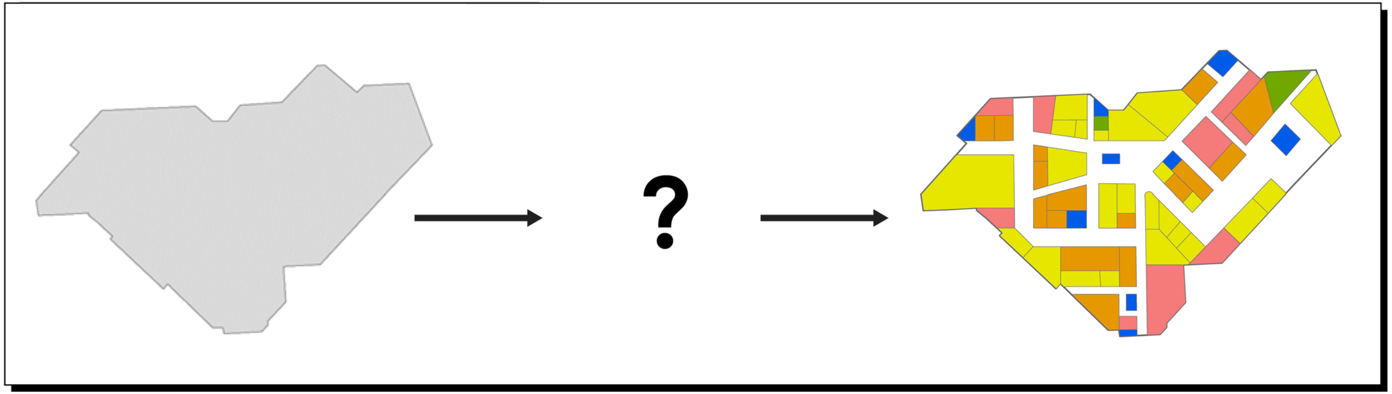
Architectural Layout Synthesis

"Crowd-driven Mid-scale Layout Design", *SIGGRAPH 2016*
Tian Feng, Lap-Fai Yu, Sai-Kit Yeung, KangKang Yin, Kun Zhou



Synthesis

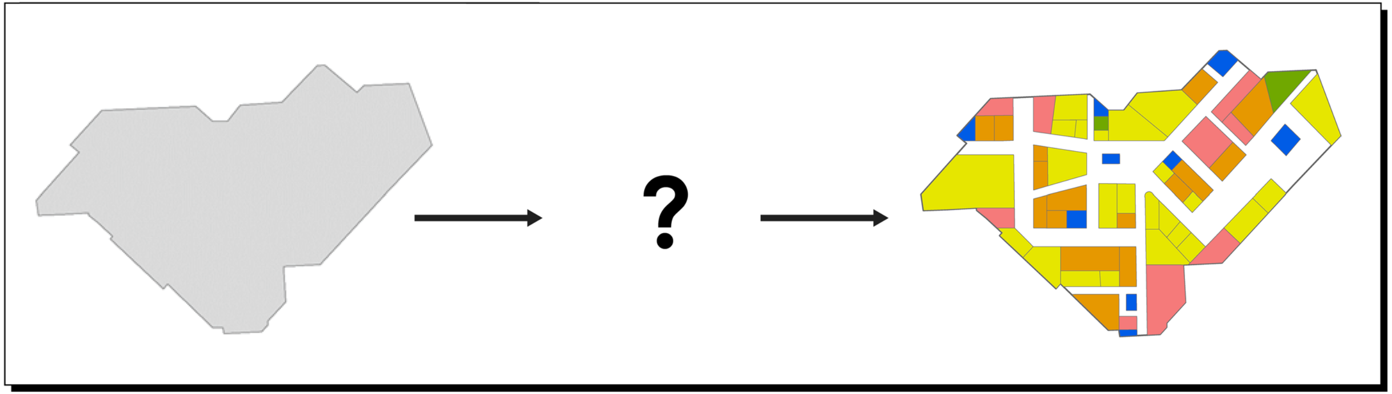
Architectural Layout Design



Input
- Layout domain
- Possible sites
  (e.g., boutiques, restaurants, restrooms)

Output
- Floor plan

Architectural Layout Design



Input
- Layout domain
- Possible sites

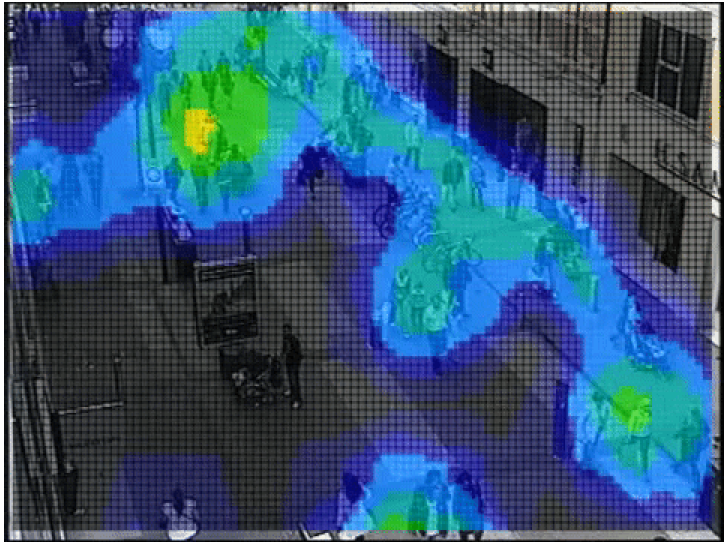
  (e.g., boutiques, restaurants, restrooms)

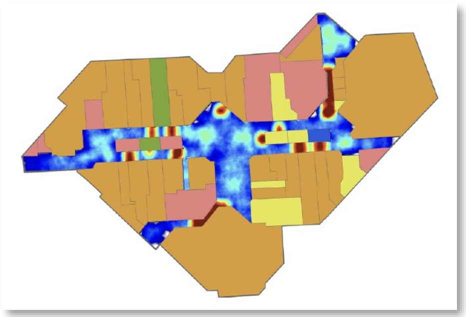
Design Goals?
Incorporating Human Factors

Output
- Floor plan

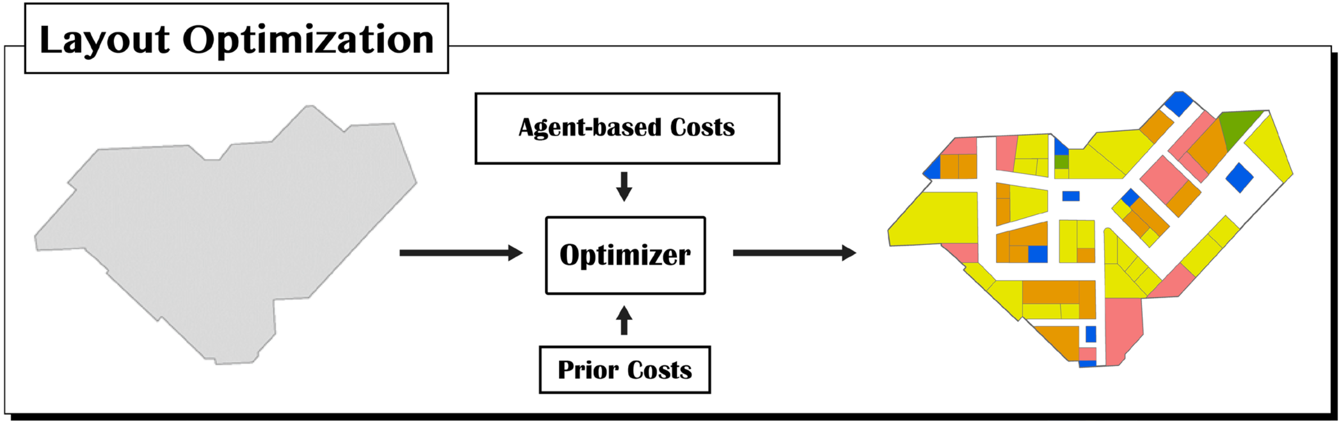
Crowd Simulation

- Typical Metric: Crowd Density
- Traditional: Evaluation
- Ours: Evaluation + Optimization





Layout Optimization



$$C(\phi) = \mathbf{C}_\mathrm{A}\mathbf{w}_\mathrm{A}{}^T + \mathbf{C}_\mathrm{P}\mathbf{w}_\mathrm{P}{}^T$$

$\mathbf{C}_\mathrm{A}$: Agent-based Cost (Mobility, Accessibility, Coziness) — Computed by agent-based simulation

$\mathbf{C}_\mathrm{P}$: Prior Cost (Floor Area Ratio, Total # of sites, # of each type of sites) — Computed by real world layouts' statistics

Mobility: how smooth is the agents' walking experience

Low Cost

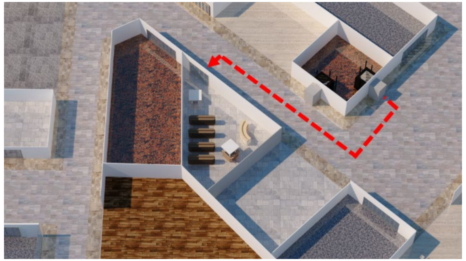
High Cost

actual speed

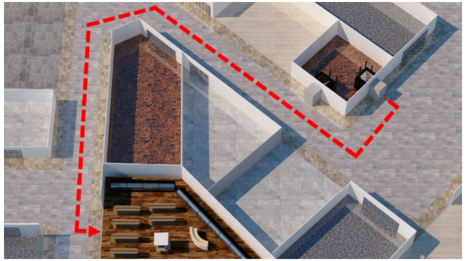
$$C_{\mathrm{m}}(\phi) = 1 - \frac{1}{N} \sum_i \frac{\bar{v}_i}{d_i}$$

baseline speed

Accessibility: how reasonably sites are distributed



Low Cost

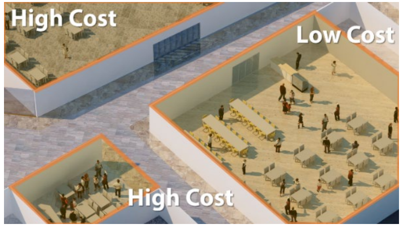


High Cost

walking distance between two sites

$$C_{\mathrm{a}}(\phi) = \frac{1}{NL} \sum_i \frac{1}{k_i} \sum_j l_{i,j}$$

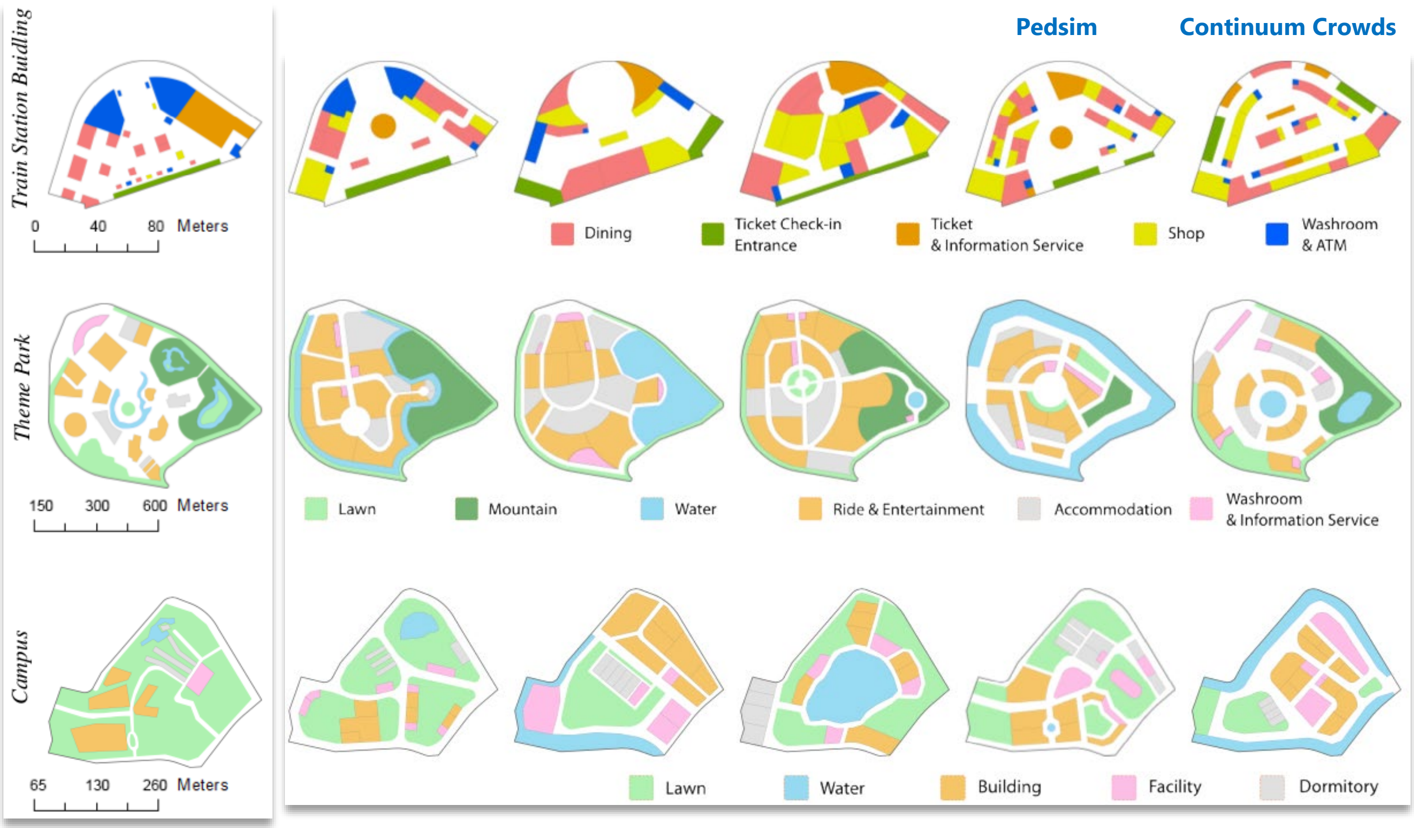
Coziness: how good agents feel in sites



crowd density in the site being visited

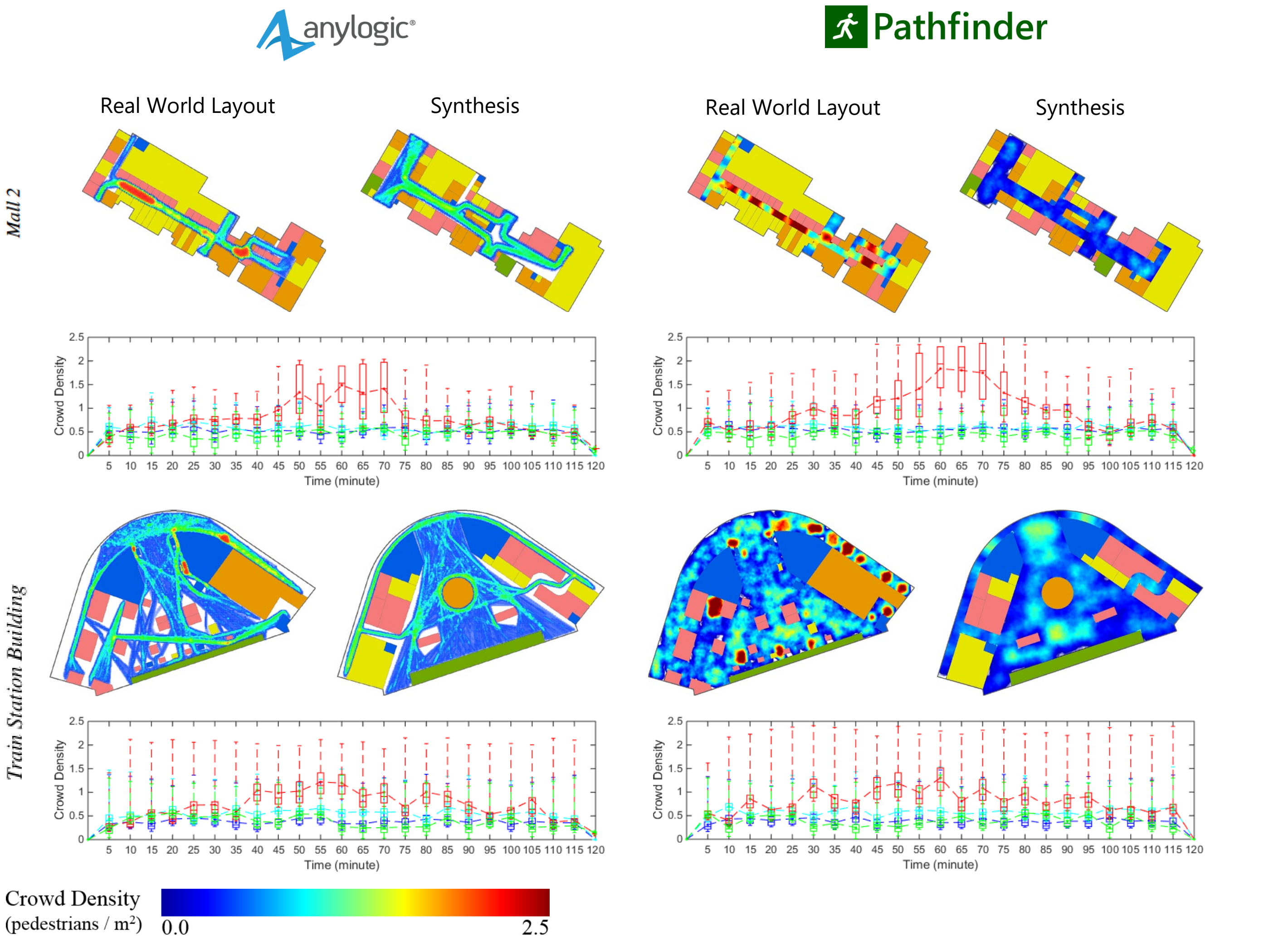
$$C_{\mathrm{c}}(\phi) = \frac{1}{N} \sum_i \frac{1}{q_i} \sum_j \left[1 - \exp\left(-\frac{(\rho_{i,j}^{\mathrm{visit}} - \mu)^2}{2\sigma^2}\right)\right]$$

Results



Real World Layout

Syntheses


anylogic
Pathfinder
Real World Layout
Synthesis
Real World Layout
Synthesis
Mall 2
Crowd Density
Time (minute)
Crowd Density
Time (minute)
Train Station Building
Crowd Density
Time (minute)
Crowd Density
Time (minute)
Crowd Density
(pedestrians / m²)
0.0
2.5

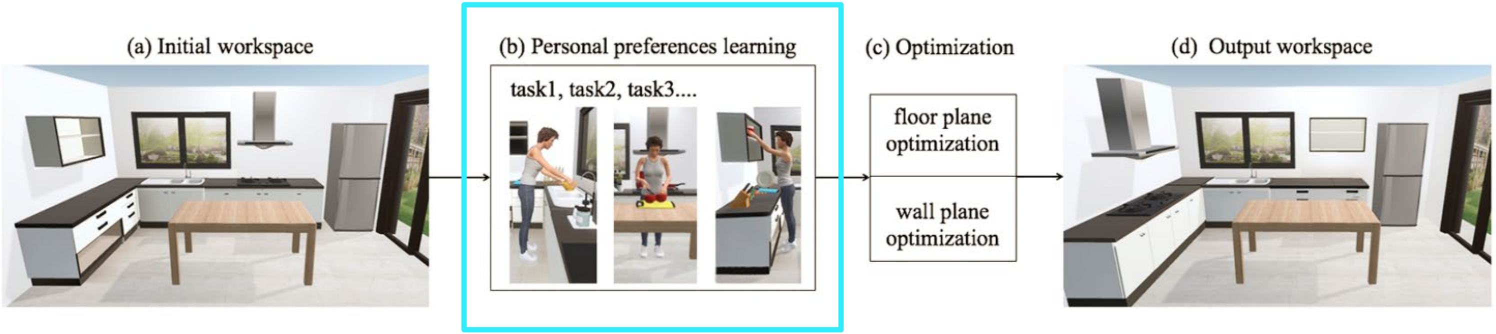
Perceptual Data-Guided Computational Design

- Human user data tracked in Virtual Reality
- Head, hand, body, eye gaze, EEG, etc.

[Courtesy of Stephan Lu]

Learning Workspace Preferences from VR

"Functional Workspace Optimization via Learning Personal Preferences from Virtual Experiences", *IEEE VR, 2019*
Wei Liang, Jingjing Liu, Yining Lang, Bing Ning, Lap-Fai Yu


(a) Initial workspace
(b) Personal preferences learning
task1, task2, task3....
(c) Optimization
floor plane optimization
wall plane optimization
(d) Output workspace

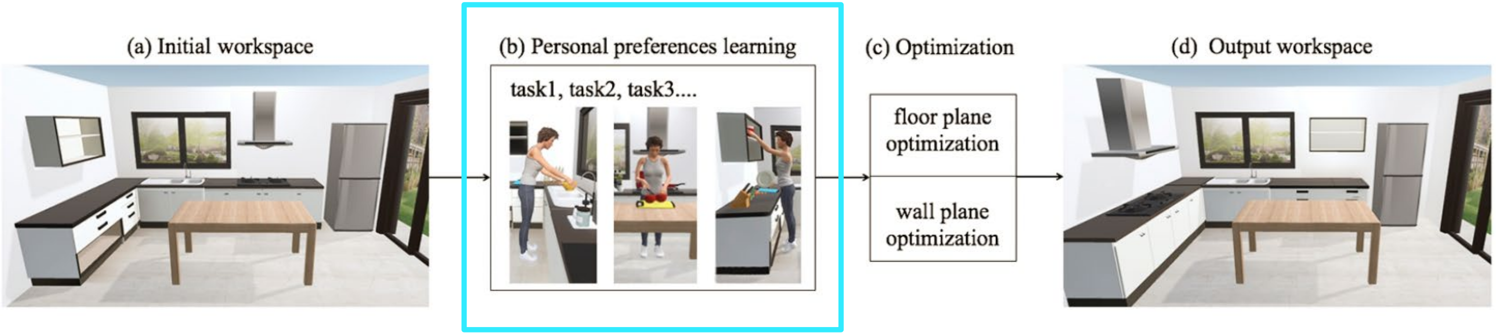


Fig. 3: An example of personal preferences. Each colored bar depicts the user interacting with the component with the same color in the scene. The ordered sequence of the components represents the personal preferences for the workflow.

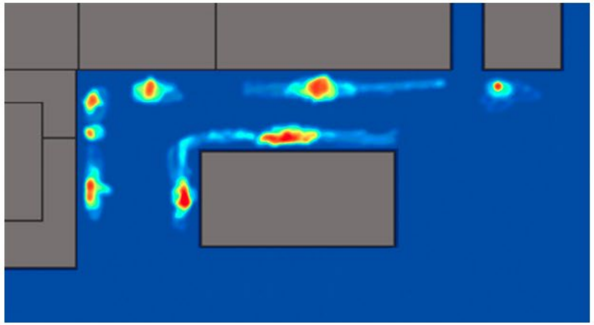
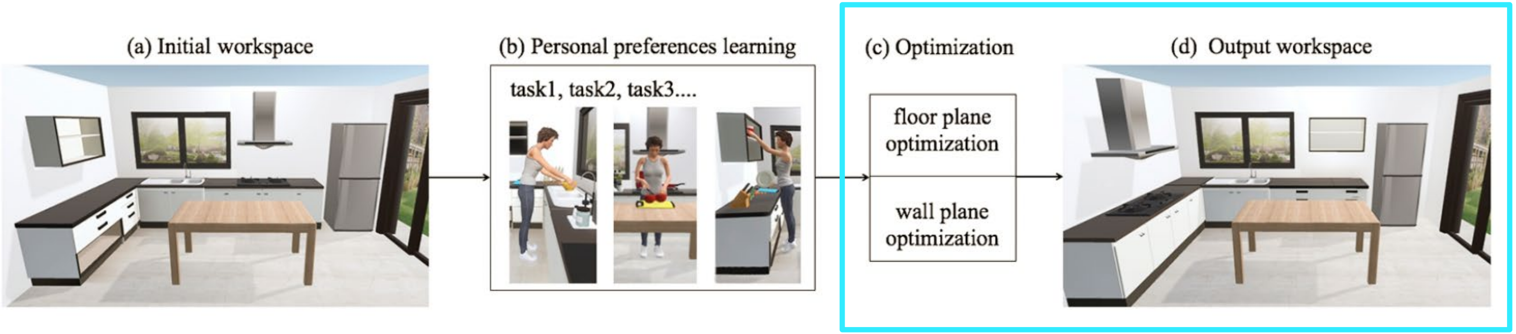


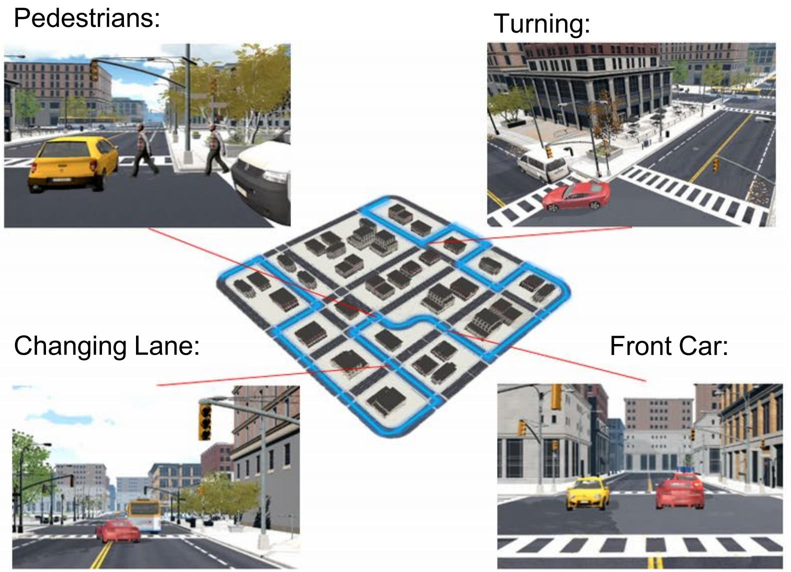
Fig. 4: The position distribution when the user interacts with the corresponding component. We use a heatmap to visualize the visited times at each point when the user interacts with the corresponding component. The redder the color is, the more times the user visited that point.

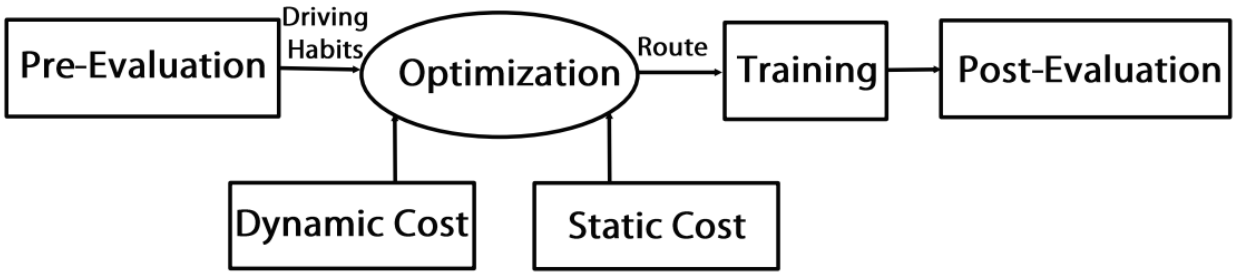

(a) Initial workspace
(b) Personal preferences learning
task1, task2, task3....
(c) Optimization
floor plane optimization
wall plane optimization
(d) Output workspace

Personalized VR Driving Training

"Synthesizing Personalized Training Programs for Improving Driving Habits via Virtual Reality", *IEEE VR, 2018*

Yining Lang, Wei Liang, Fang Xu, Yibiao Zhao, Lap-Fai Yu

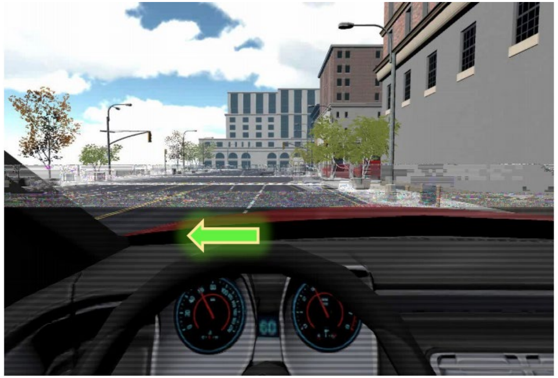




Driving Habits:

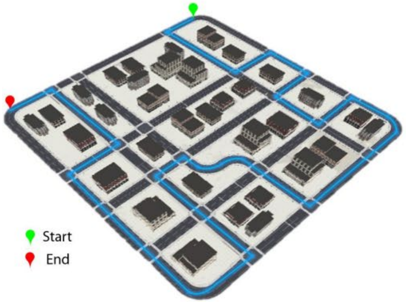
Signal before a Turn

Signal before Changing Lane

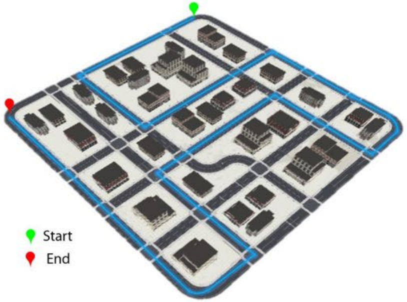


Stop for Pedestrians

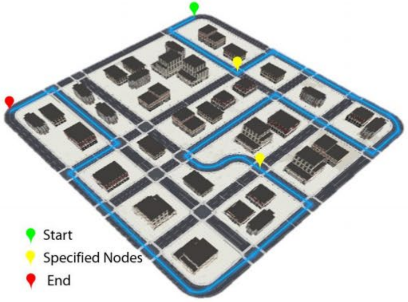
Optimized Training Routes:



(a) More Turns



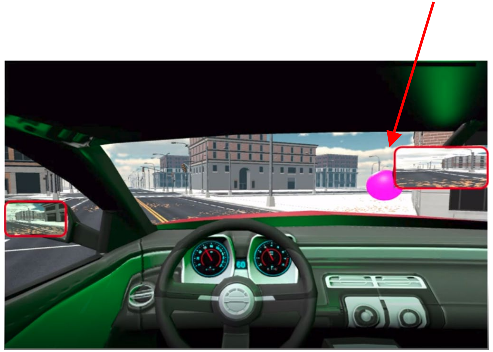
(b) Fewer Turns



(c) Pass Specified Positions

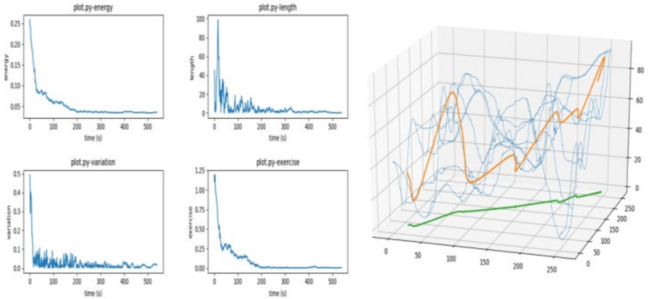
VR Training:

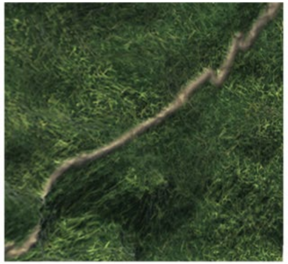
Gaze tracked in VR



Terrain Generation for VR Biking

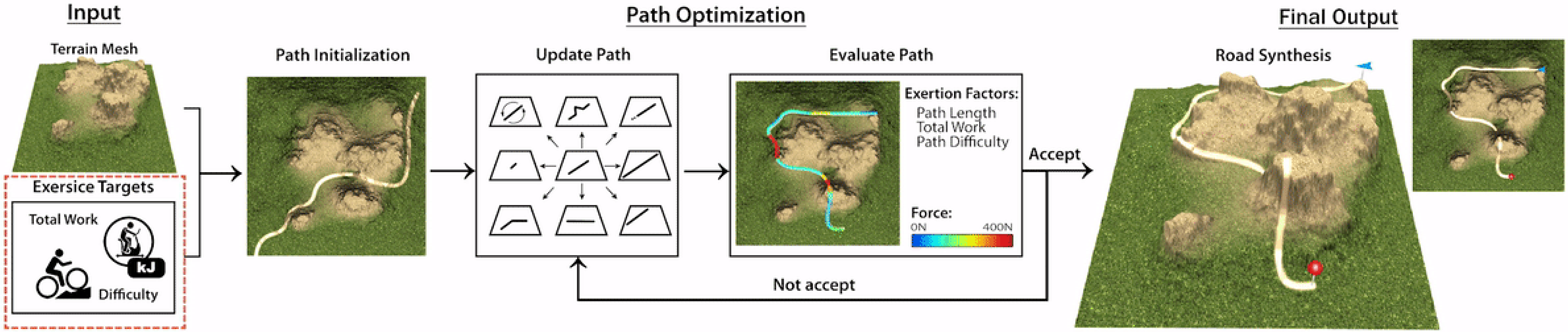
Fitbit VR bike:



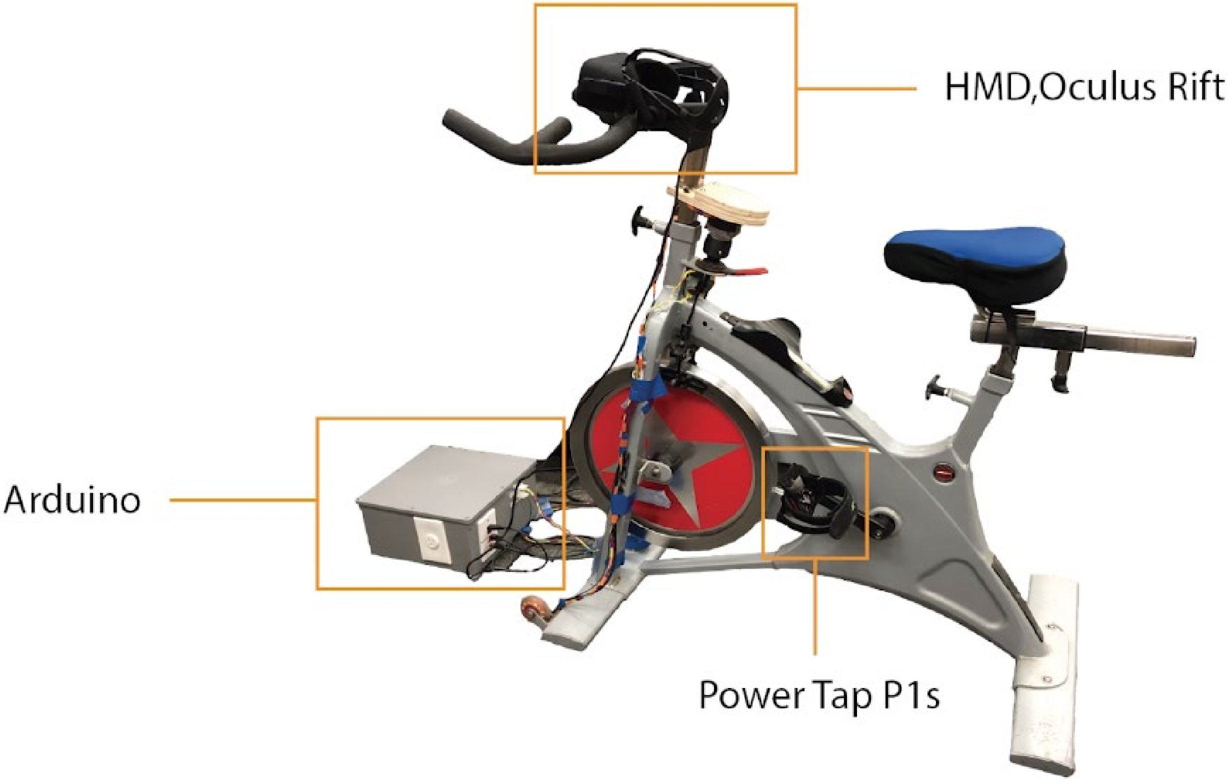


"Exertion-Aware Path Generation", *SIGGRAPH 2020*
Wanwan Li, Biao Xie, Yongqi Zhang, Walter Meiss, Haikun Huang, Lap-Fai Yu

Overview



Input
Terrain Mesh
Exersice Targets
Total Work
kJ
Difficulty
Path Initialization
Path Optimization
Update Path
Evaluate Path
Exertion Factors:
Path Length
Total Work
Path Difficulty
Force:
0N
400N
Accept
Not accept
Final Output
Road Synthesis

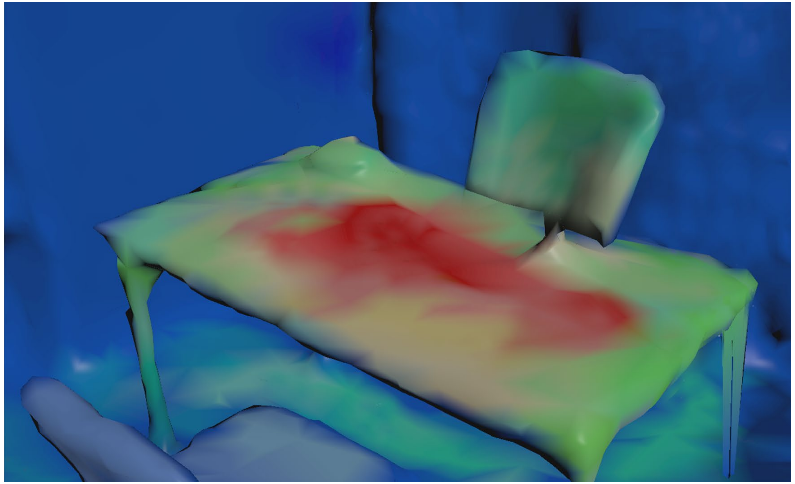

HMD,Oculus Rift
Arduino
Power Tap P1s

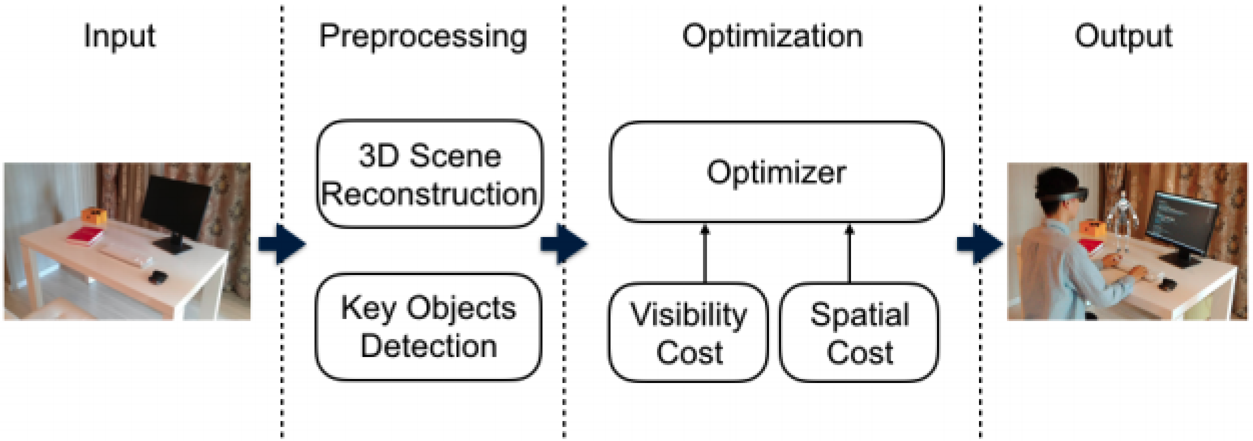
VR Exercise Biking

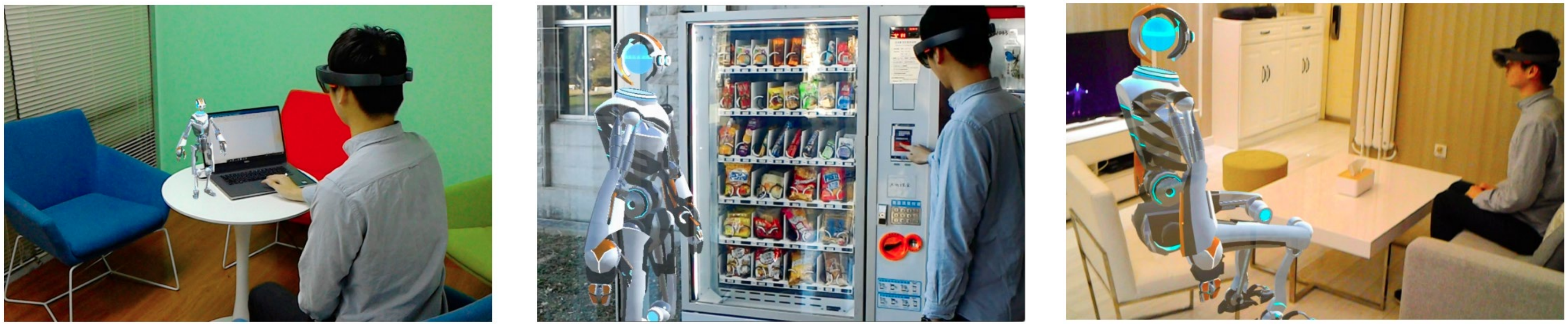
Scene-Aware Virtual Agents

Virtual Agent Positioning

"Virtual Agent Positioning Driven by Scene Semantics in Mixed Reality", *IEEE VR, 2019*
Yining Lang, Wei Liang, Lap-Fai Yu

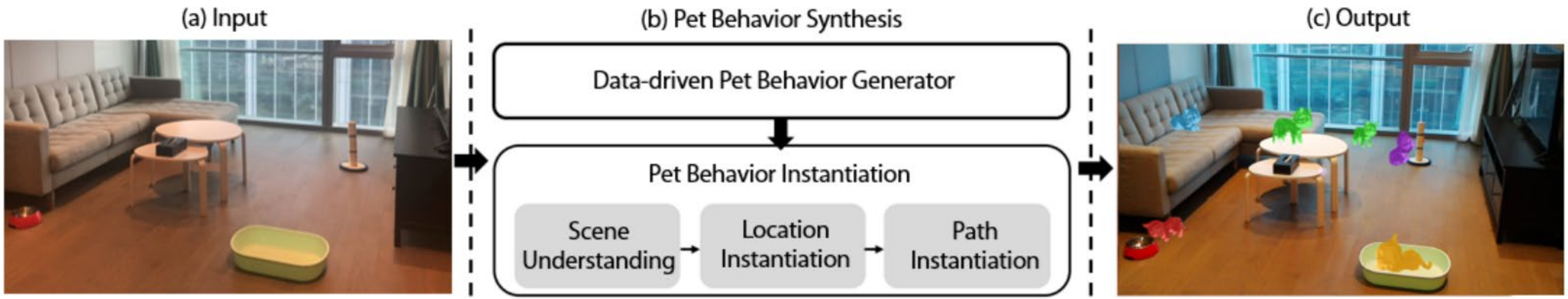


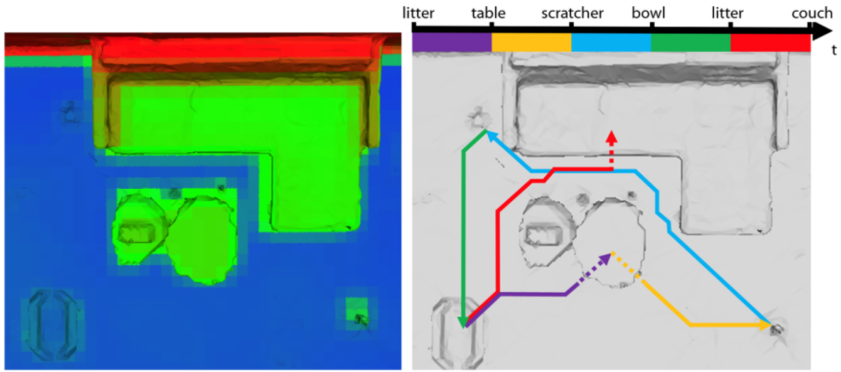

Input
Preprocessing
Optimization
Output
3D Scene Reconstruction
Key Objects Detection
Optimizer
Visibility Cost
Spatial Cost



Virtual Pet Synthesis

"Scene-Aware Behavior Synthesis for Virtual Pets in Mixed Reality", *ACM CHI 2021*
Wei Liang, Xinzhe Yu, Rawan Alghofaili, Yining Lang, Lap-Fai Yu


(a) Input
(b) Pet Behavior Synthesis
(c) Output
Data-driven Pet Behavior Generator
Pet Behavior Instantiation
Scene Understanding
Location Instantiation
Path Instantiation



(a) Path geometry cost.

(b) Optimized paths.

Fig. 6. (a) A visualization of the path geometry cost for each cell. The redder a cell is, the higher its cost value is. (b) An illustration of the optimized paths. The state bar at the top shows the sequence of objects that the pet travels to. Each color refers to a path going from one object's location to another object's location (e.g., purple refers to going from the litter to the table).

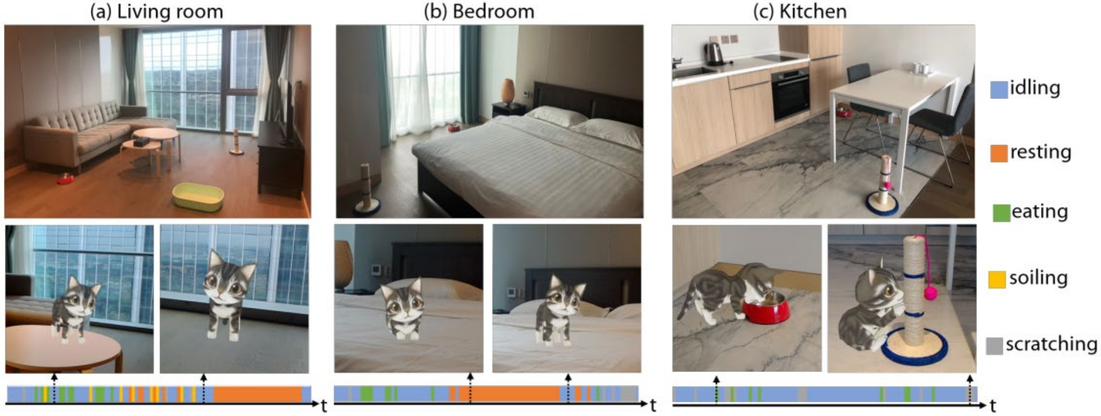


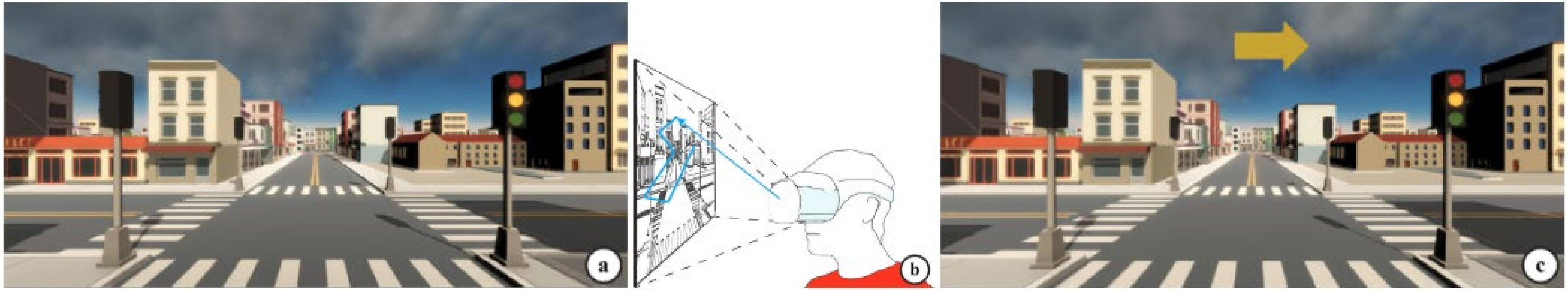
Fig. 7. The living room, bedroom, and kitchen scenes used in our experiments. The top row shows the input scene. The middle row demonstrates some generated behaviors. The bottom row shows the generated behavior sequence visualized by a state bar. Each sequence consists of 100 behaviors and each behavior is shown by one color in the bar.

Navigation Aid

Adaptive VR Navigation Aid

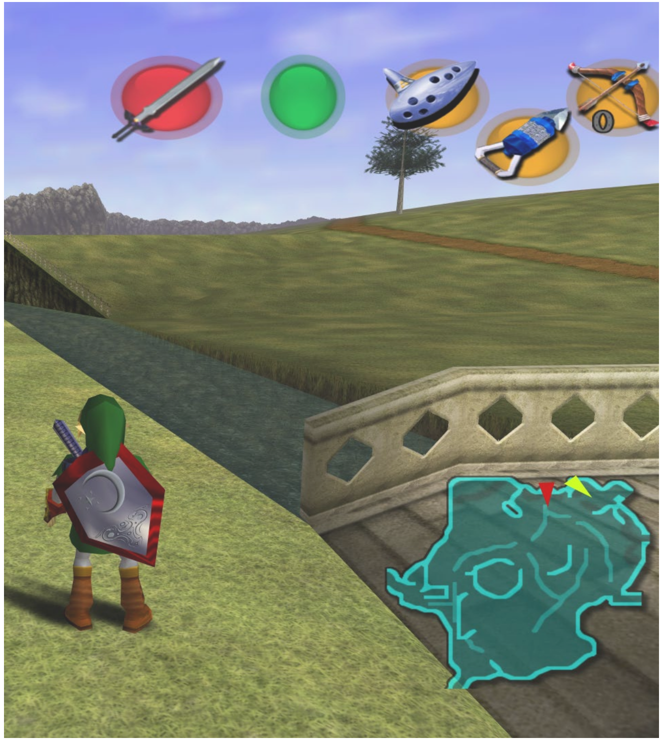
"Lost in Style: Gaze-Driven Adaptive Aid for VR Navigation", *CHI 2019*

Rawan Alghofaili, Yasuhito Sawahata, Haikun Huang, Hsueh-Cheng Wang, Takaaki Shiratori, Lap-Fai Yu

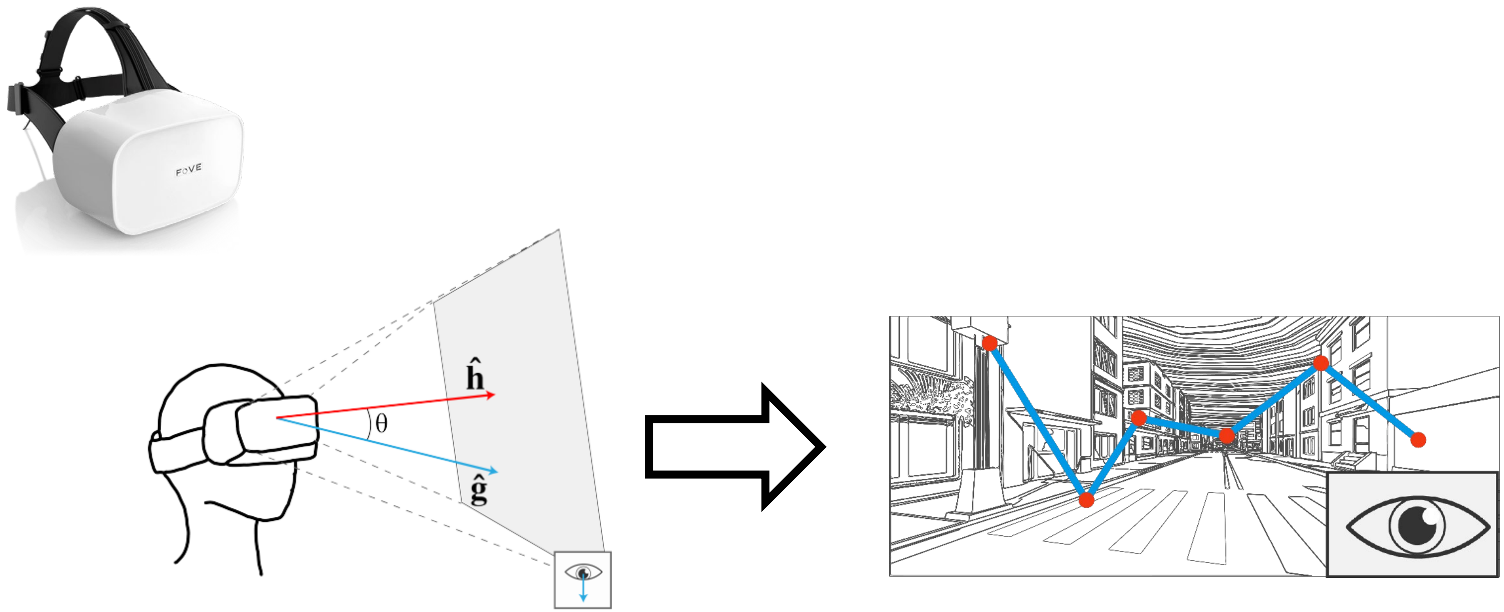


Navigation Aids in Virtual Worlds

Arrow

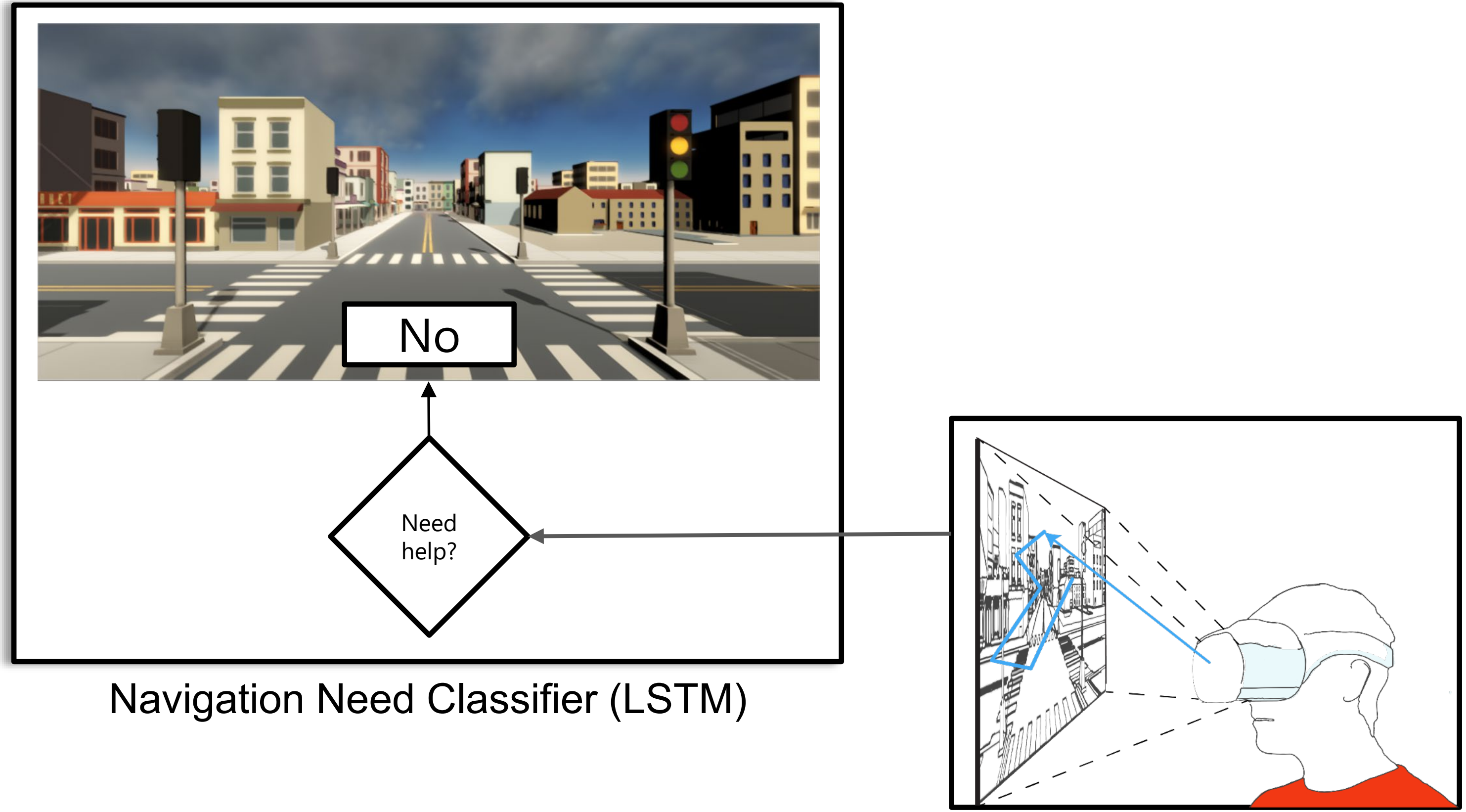


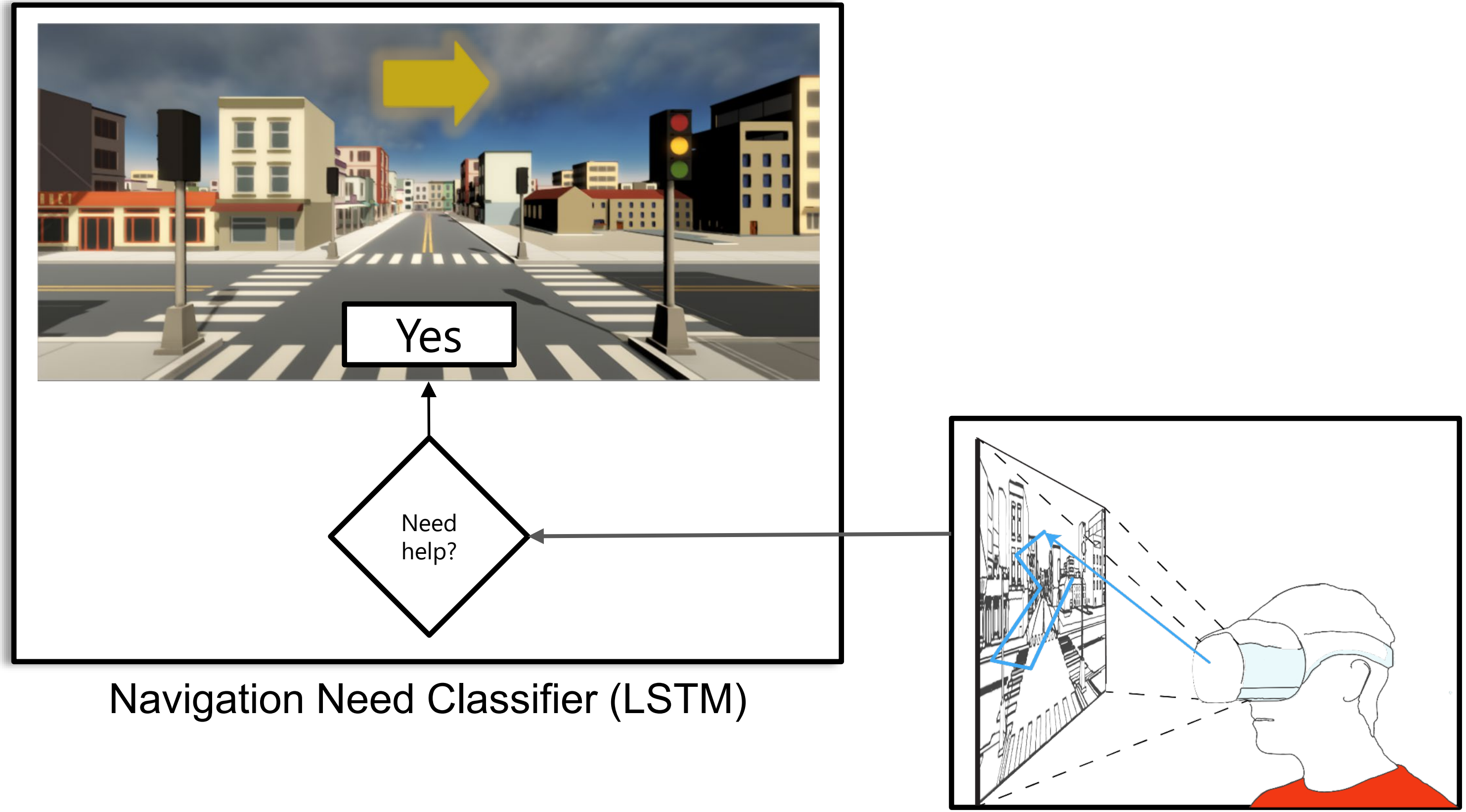
Mini Map

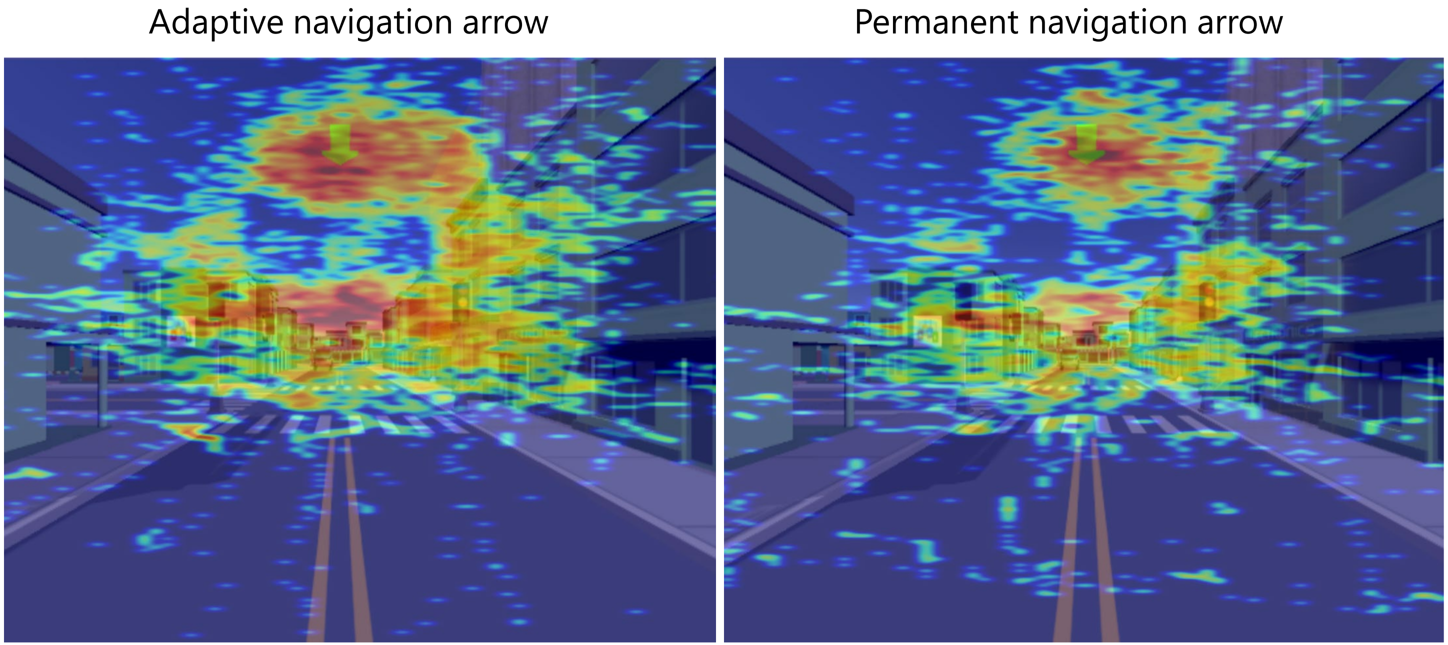


FOVE VR eye-tracking headset

Eye-tracking gaze sequences


No
Need
help?
Navigation Need Classifier (LSTM)


Yes
Need help?
Navigation Need Classifier (LSTM)


Adaptive navigation arrow
Permanent navigation arrow

Dawn of VR/AR gaming

- What will be the de facto tools / techniques?

Game designer's end	Player's end
content creation / authoring	interaction
level design	user interface
animation	collaboration
gameplay / genres	communication


MARIO
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TIME
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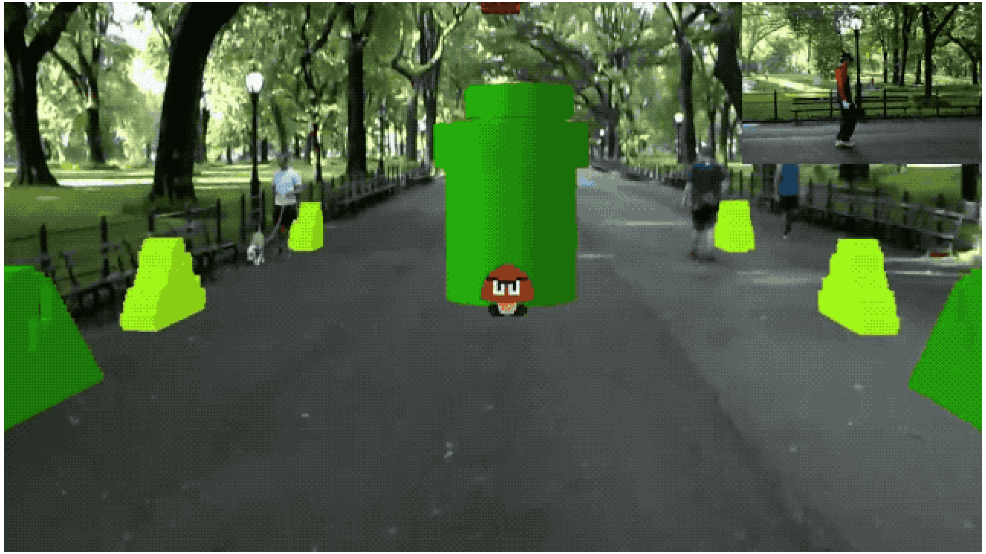
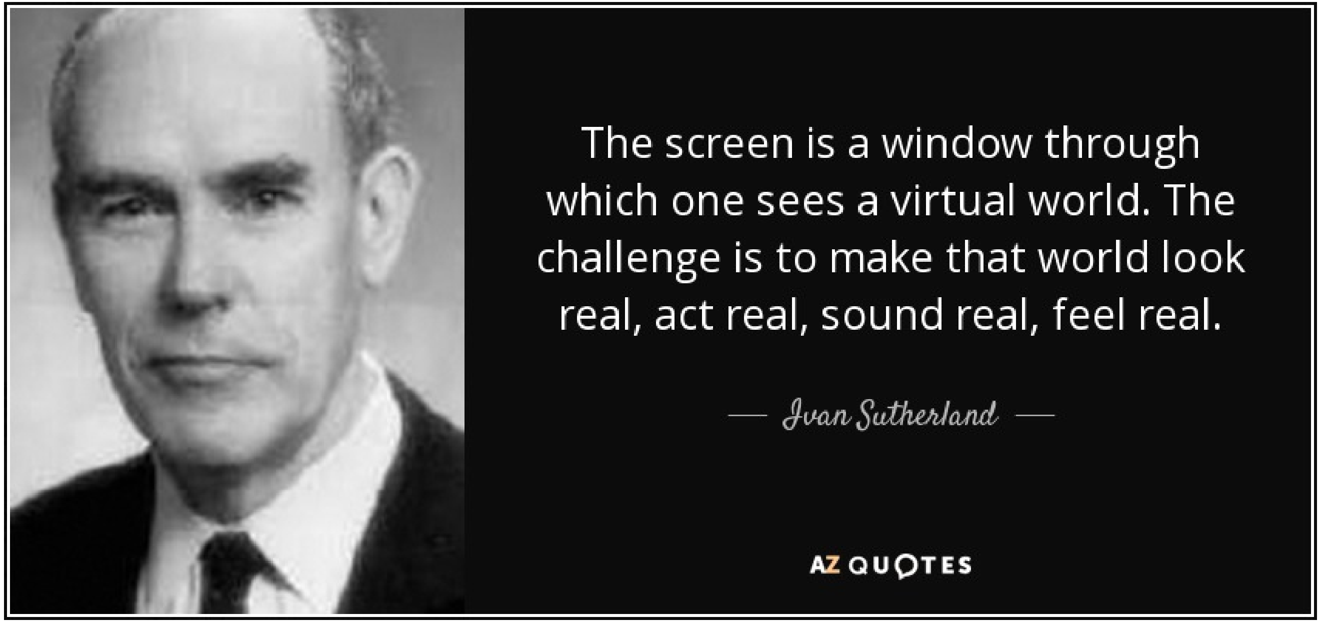


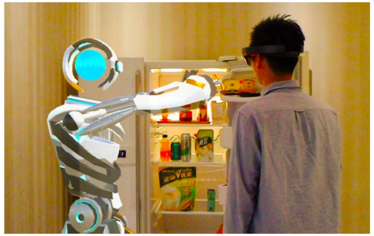
4 Reals of VR


The screen is a window through which one sees a virtual world. The challenge is to make that world look real, act real, sound real, feel real.
— Ivan Sutherland —
AZ QUOTES

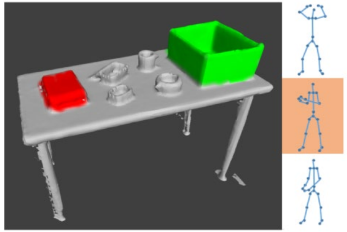
Real yet?

Act real?

AR Agent Positioning [VR 19]

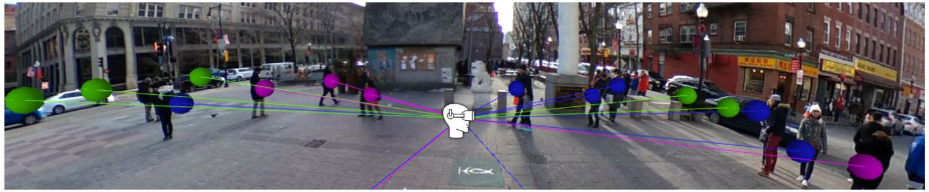


Affordance Reasoning [ICCV 17]



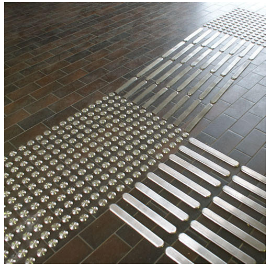
Sound real?

Audible Panorama [CHI 19]



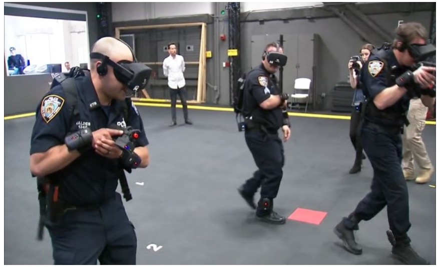
Feel real?

Tactile inference? Haptics-aware 3D synthesis?



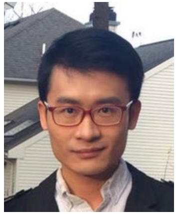
Shared realism

Multi-user VR Experiences



Acknowledgements: Students & Mentees

PhD students:


Haikun Huang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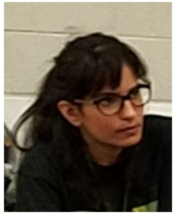
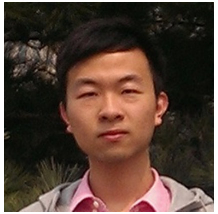
Tian Feng


Mahdi Jampour

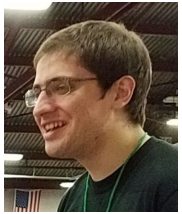

Yujia Wang


Rawan Ghofaili


Changyang Li


Wanwan Li

MS students: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Please check out my research website
for many projects and demos!

https://cs.gmu.edu/~craigyu/