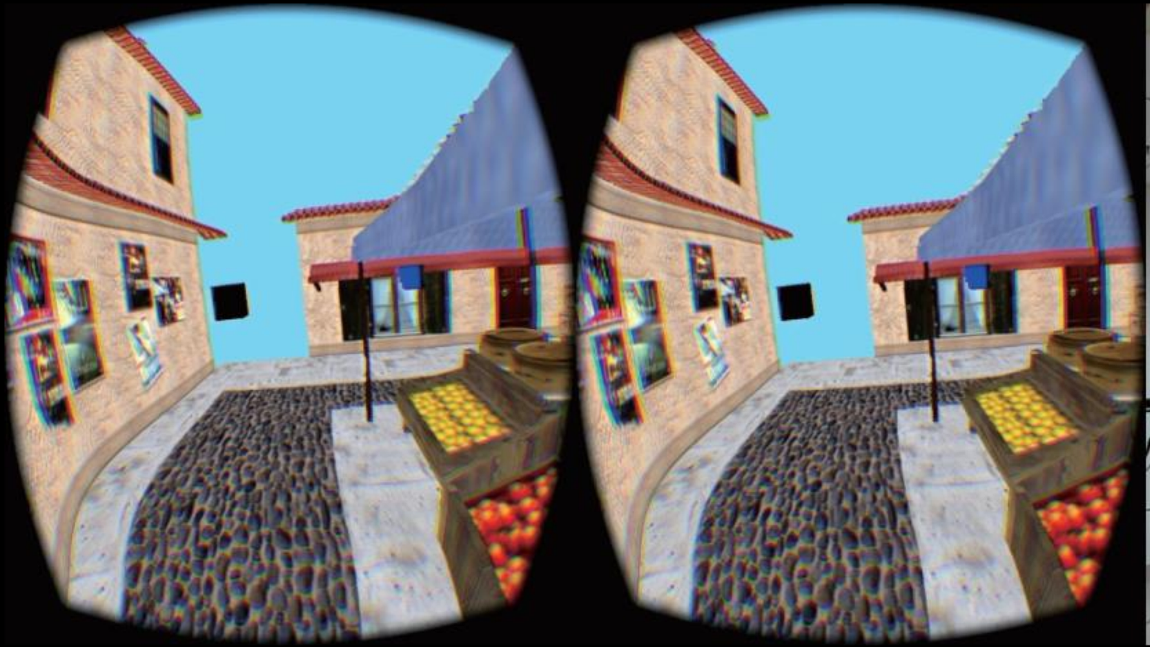

Smooth Assembled Mappings for Large-Scale Real Walking

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Immersive virtual reality

- A perception of being physically present in a **non-physical** world
- VR systems provide an **engrossing** total environment

HTC Vive

Oculus Rift

Sony Play Station

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Locomotion in immersive VR

- **Joystick**
- Walking-in-place
- Real walking

stationary, unnatural

Locomotion in immersive VR

- Joystick
- **Walking-in-place**
- Real walking

simulated walking, less natural

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Locomotion in immersive VR

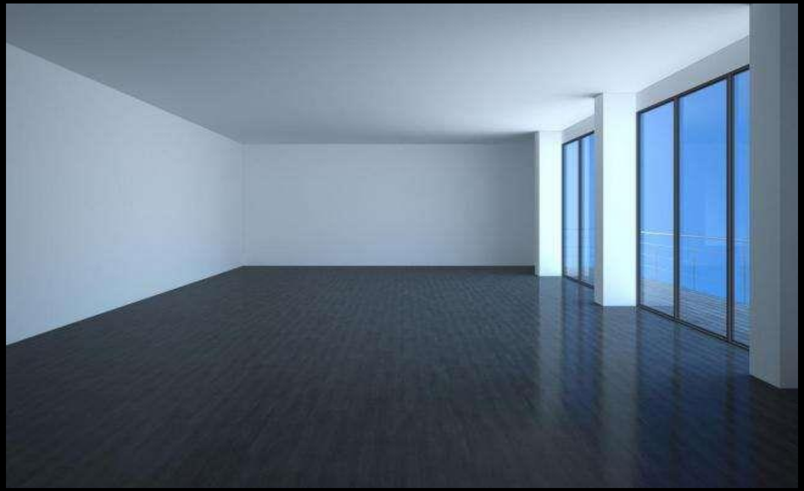
- Joystick
- Walking-in-place
- **Real walking**

walk freely, natural

Goal: mapping for real walking

- Build a **mapping** between the virtual scene and the real workspace
- Optimal: **bijective and isometric** mapping

Virtual scene

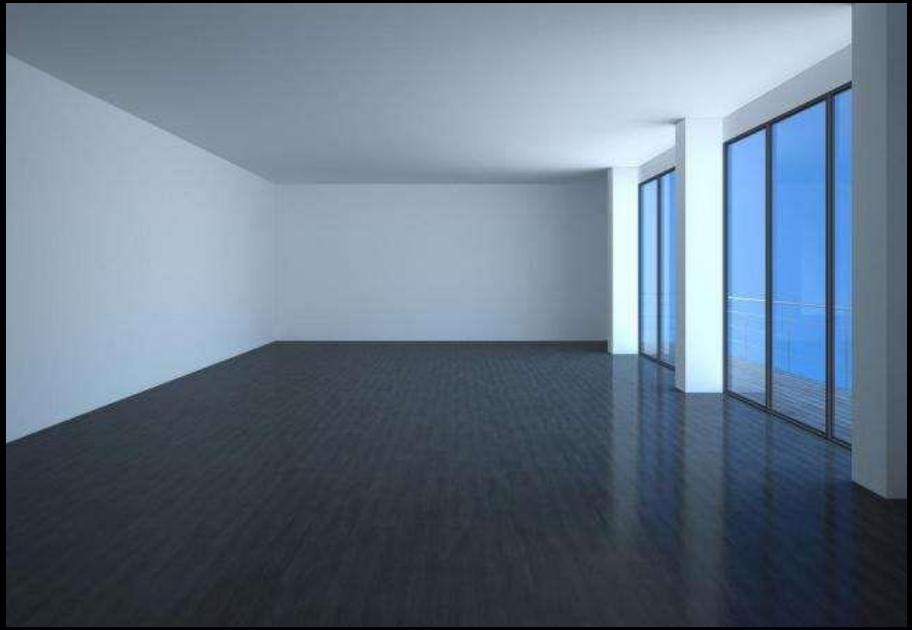


Real workspace

Challenge

- Virtual scene and real workspace often differ significantly in **sizes**, **shapes**.
- How to explore **large** virtual scene in **smaller** real workspace?

Virtual scene



Real workspace

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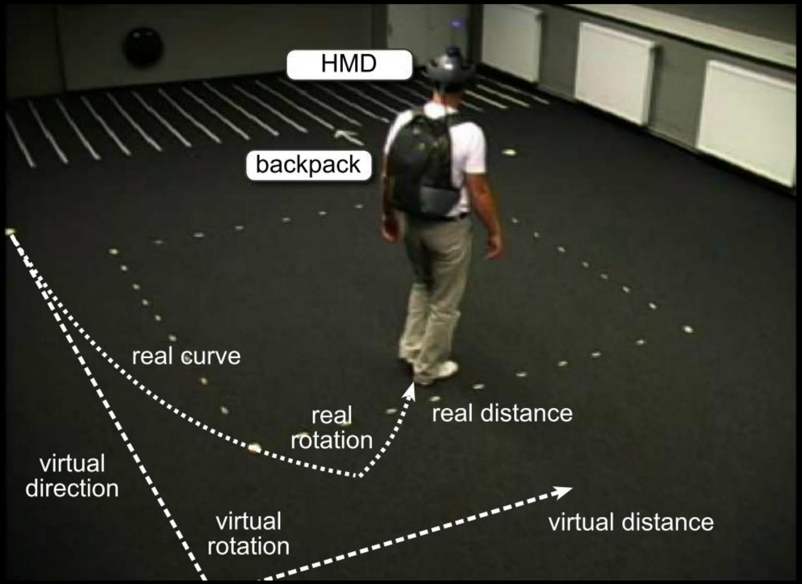
Existing methods in real walking

- Space manipulation
  - [Suma et al. 2011, 2012], [Vasylevska and Kaufmann 2017], [Vasylevska et al. 2013]

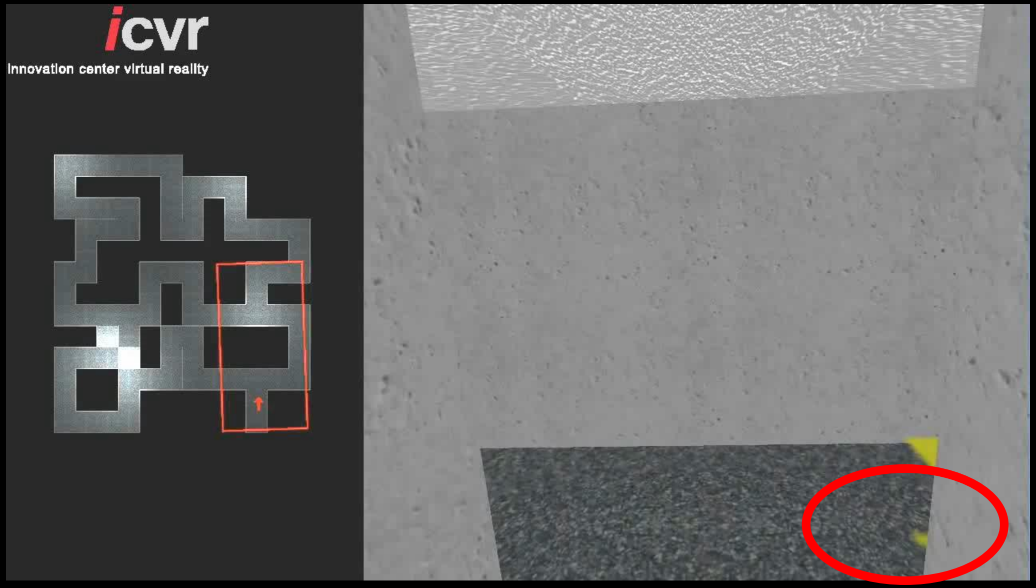
[Vasylevska et al. 2013]

Existing methods in real walking

- Redirected walking
  - [Razzaque et al. 2001, 2002], [Williams et al. 2007], [Steinicke et al. 2010],[Hodgson and Bachmann 2013], [Azmandian et al. 2014], [Nescher et al. 2014] ···



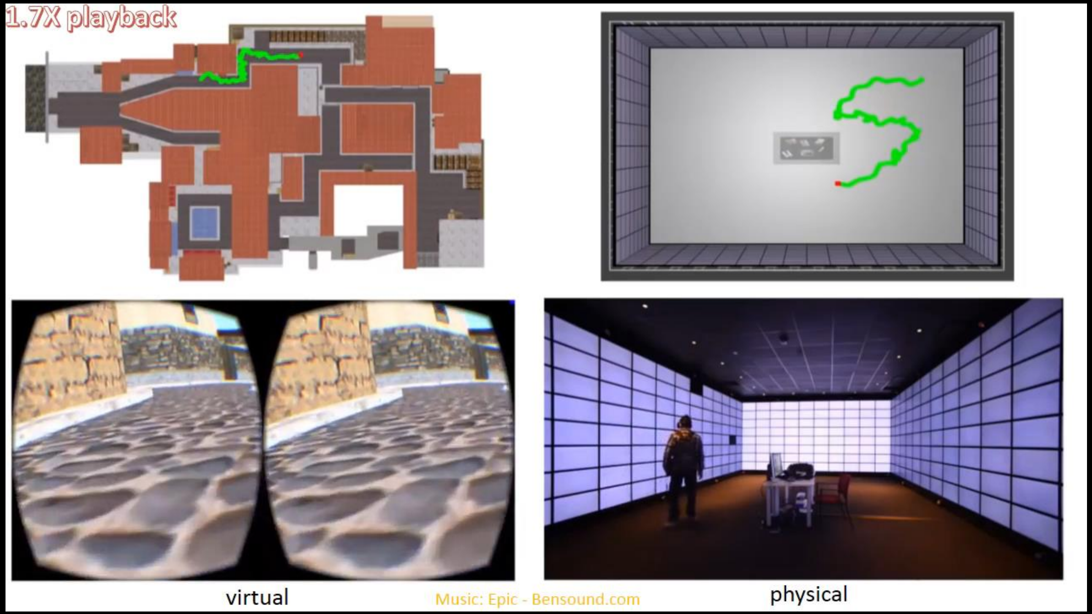
[Steinicke et al. 2010]



[Nescher et al. 2014]

Existing methods in real walking

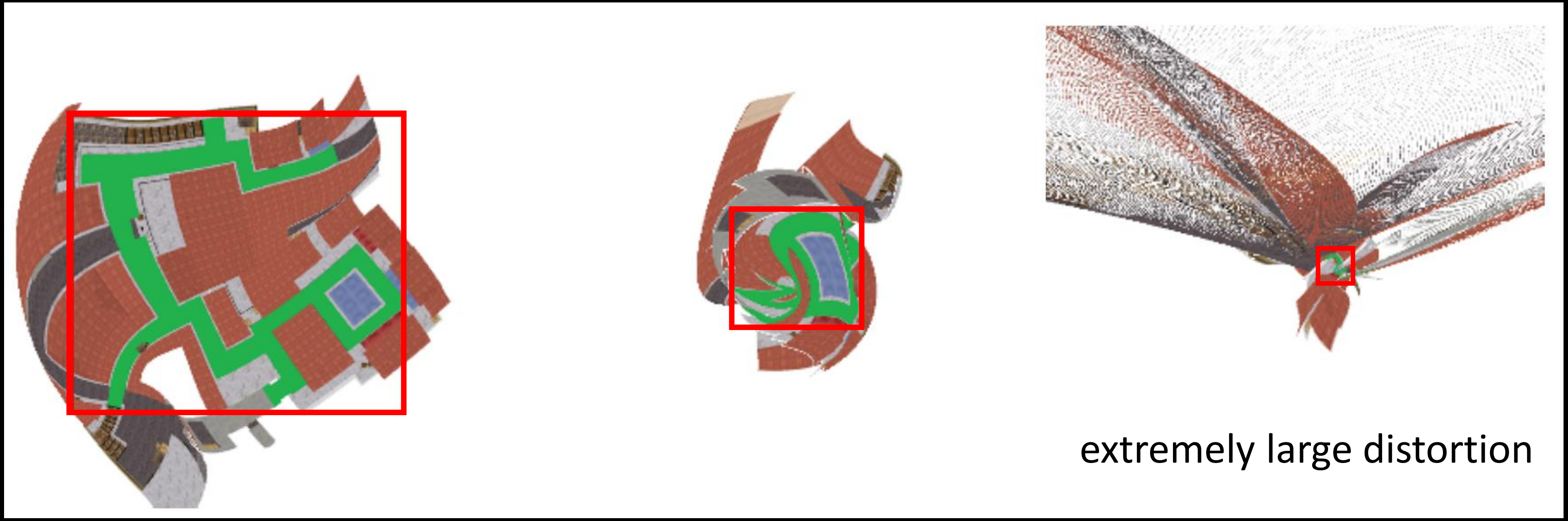
- Space mapping method
  - [Sun et al. 2016] : computing a global mapping between virtual and real scenes



[Sun et al. 2016]

Problem: severe distortion

- Mapping the **large-scale** virtual scene **globally** may result in severe distortions and artifacts.



The greater size ratio, the larger distortions

Our idea

- **S**mooth **A**ssembled **M**appings (**SAM**):
  - A **divide-and-conquer** strategy

- Benefits:

  ✓map substantially large virtual scenes into smaller real workspaces with low isometric distortion

  ✓achieve better walking experience

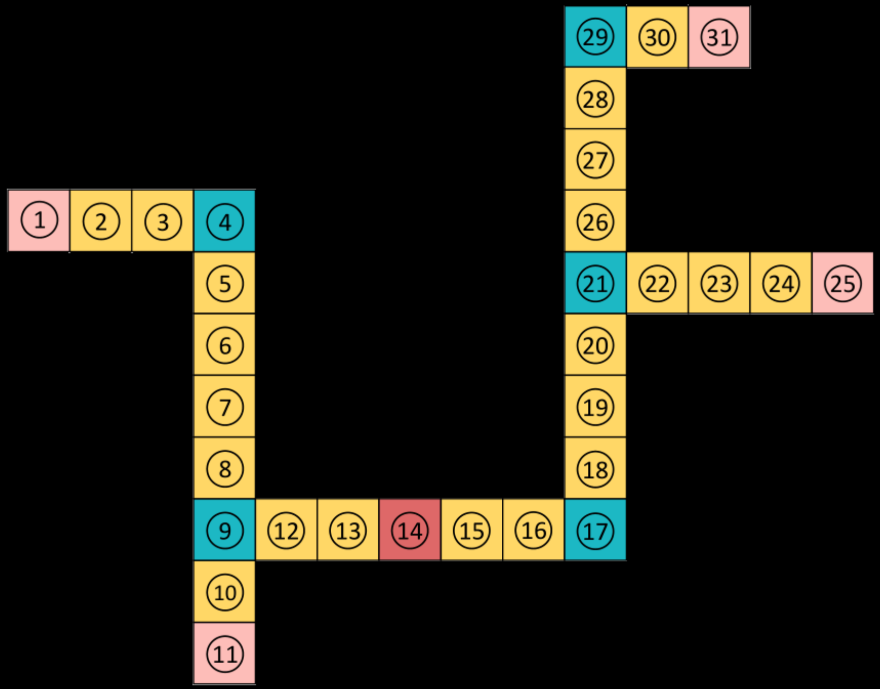
Our Method

1. Decomposition
   - Decompose the virtual scene into small super-patches
2. Mapping assembly
   - Each super-patch is mapped into real workspace
3. Global refinement
   - Reduce the distortion globally

- Key challenges:
  - How to achieve **low distortion mappings** for **large-scale** virtual scene?
  - How to keep **smoothness** between local mappings?

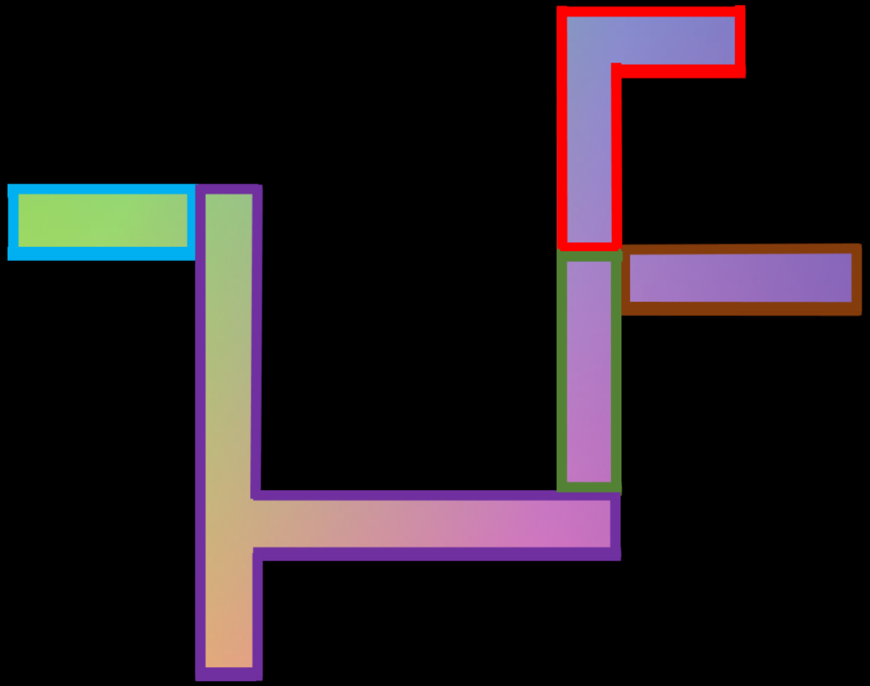
Decomposition

Input

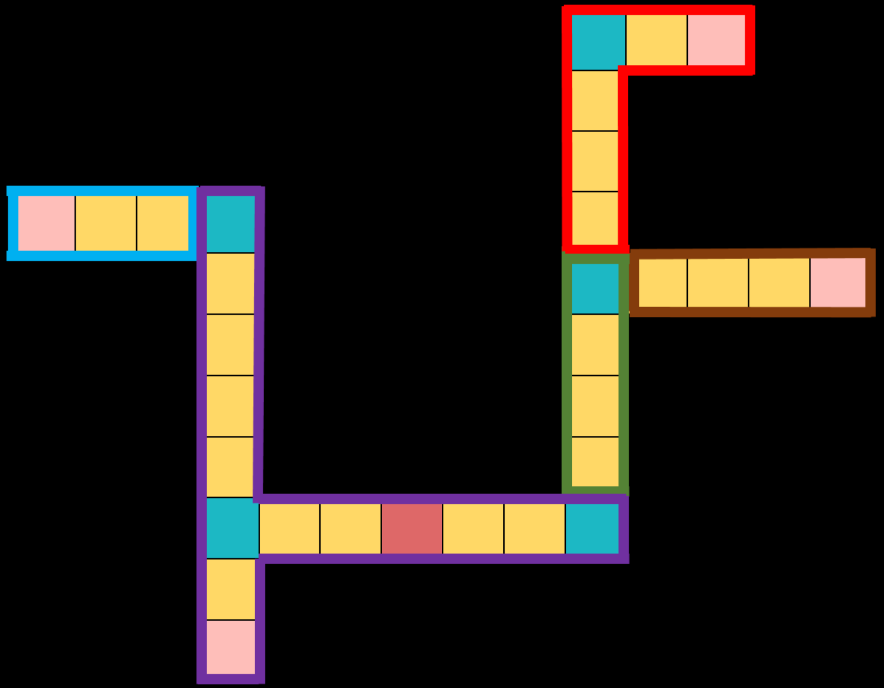


Partition patches

Decomposition



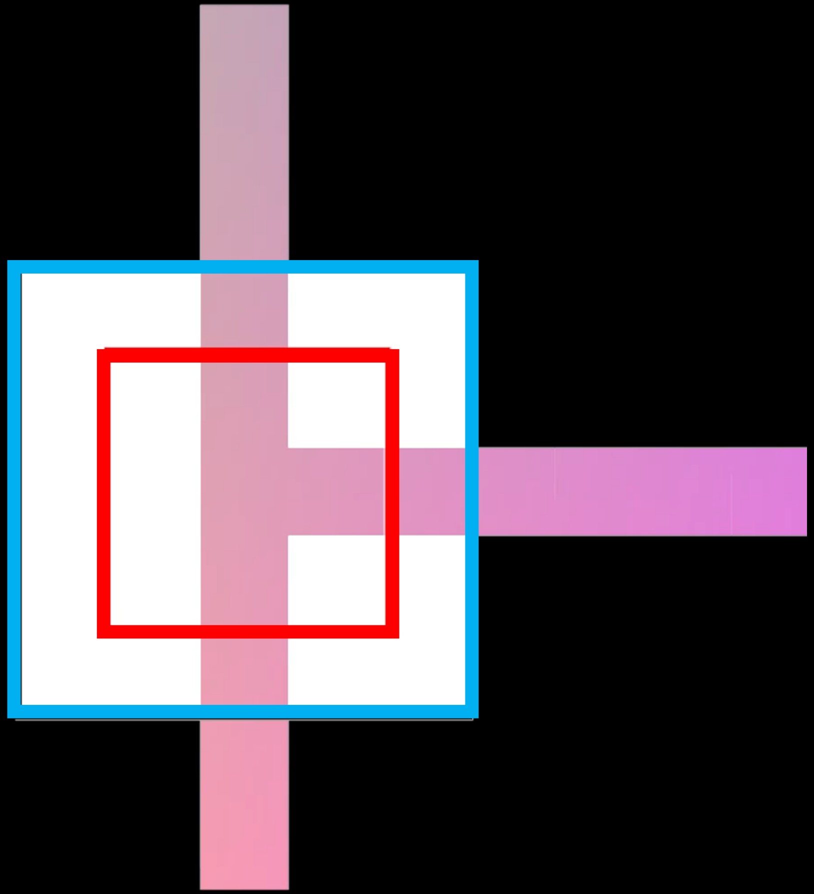
Input



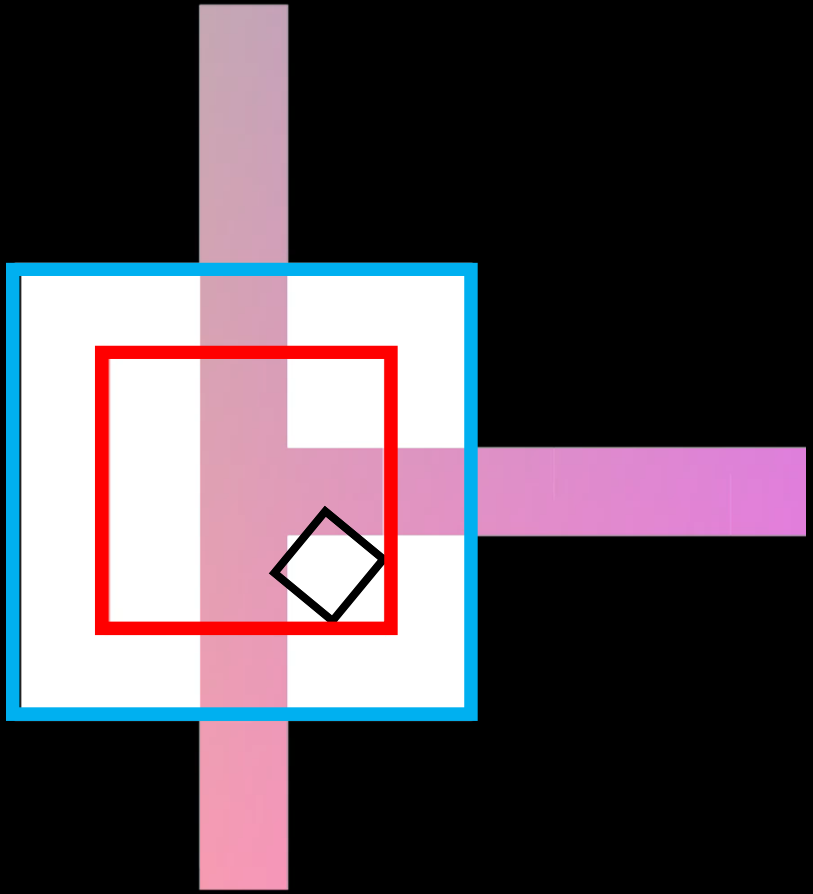
Super-patches

Mapping assembly

- Compute mappings for all super-patches one by one in a width-first order.



The first super-patch



Mapping result

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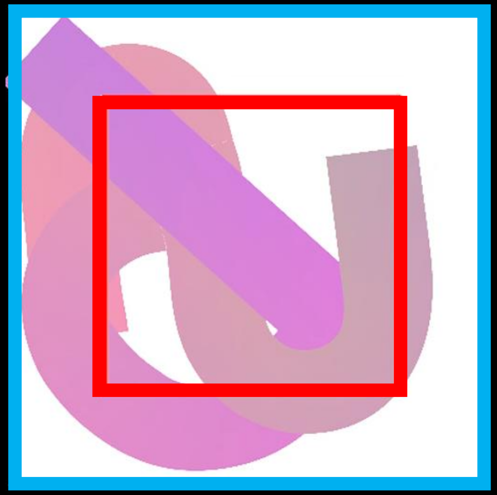
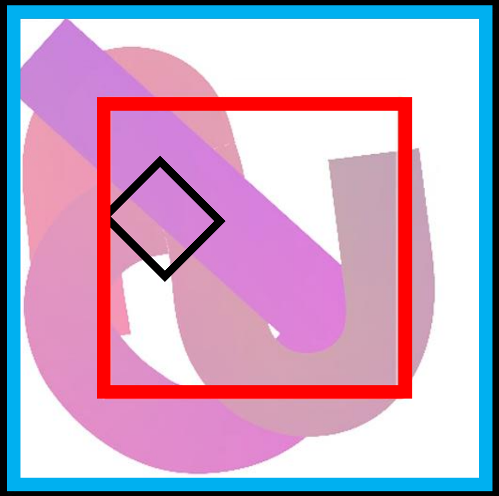
Mapping assembly

- Compute mappings for all super-patches one by one in a width-first order.



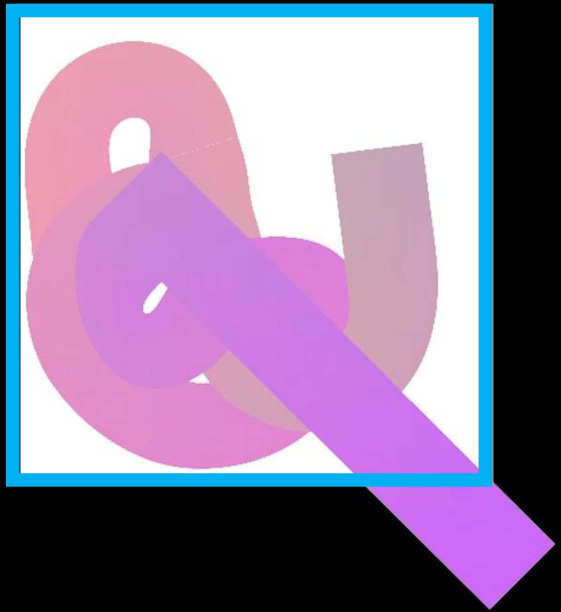
The second super-patch



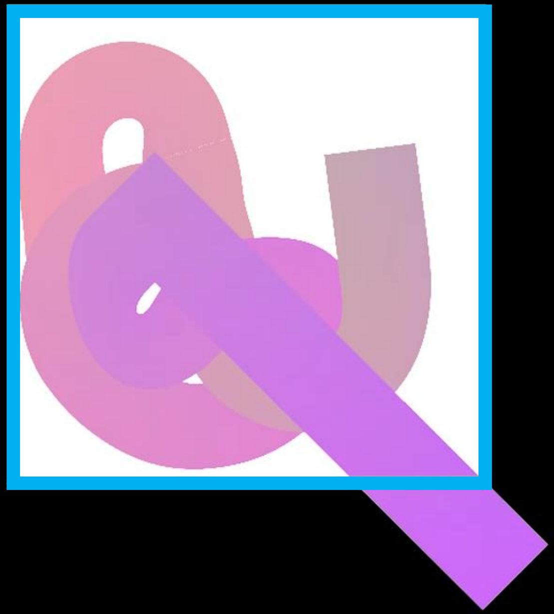
Mapping and assembly

Mapping assembly

- Compute mappings for all super-patches one by one in a width-first order.



The other super-patches



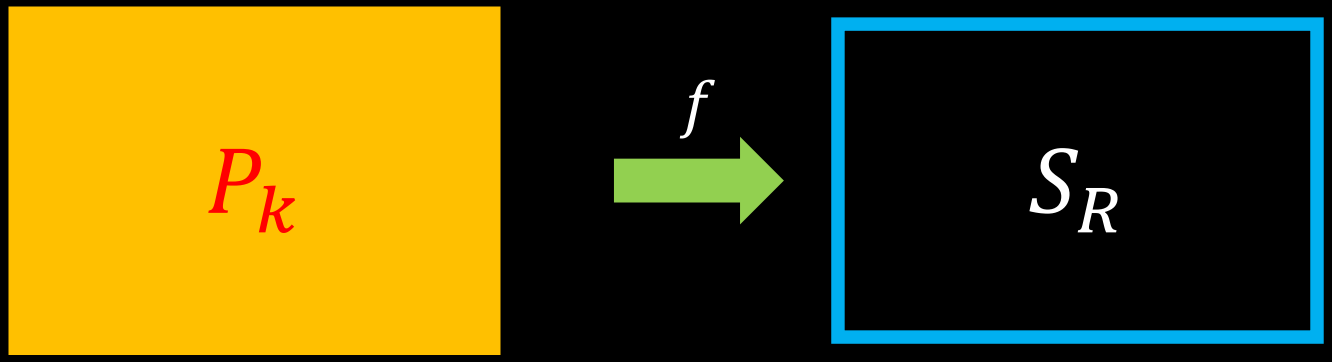
Mapping and assembly

Mapping a local quad patch

- Bézier patch as a map:

$$f(u,v) = \sum_{i=0}^{n}\sum_{j=0}^{m} c_{i,j} B_i^n(u) B_j^m(v)$$

  - ✓ $c_{i,j}$: control points
  - ✓ $B_i^n(u)$: Bernstein polynomial basis function



One patch

Real workspace

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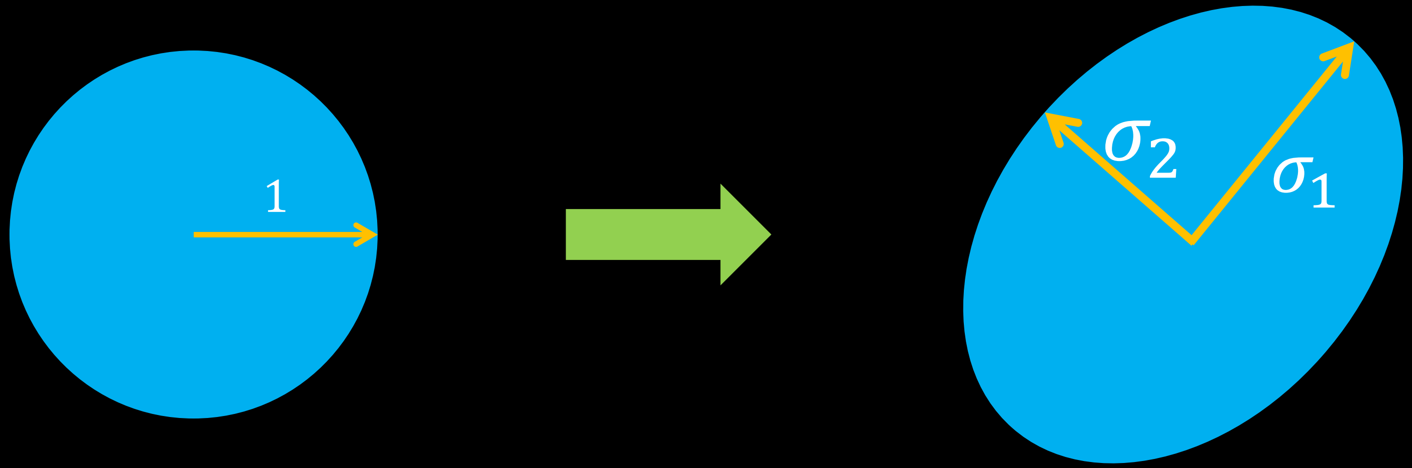
Distortion cost: conforming low-distortion mapping

- Distance-preserving cost:

$$E^{iso}(p) = \sum_{j=1}^{2} \sigma_j^2 + \sigma_j^{-2}$$

✓ σ_j: singular value of $J(p)$

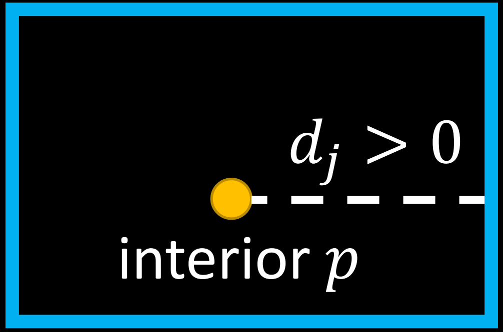
✓ When $\sigma_1 = \sigma_2 = 1$, the mapping is isometric, i.e., distance-preserving

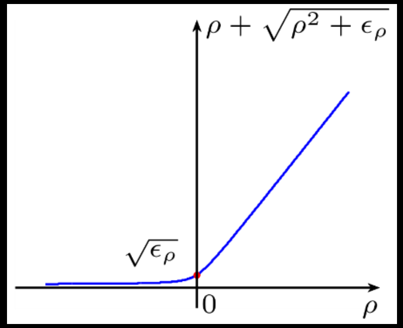


Boundary cost: avoiding colliding

- Exterior boundary cost

$$E^{ext}(p) = \sum_{j=1}^{4} \frac{2}{d_j + \sqrt{d_j^2 + \epsilon}}$$

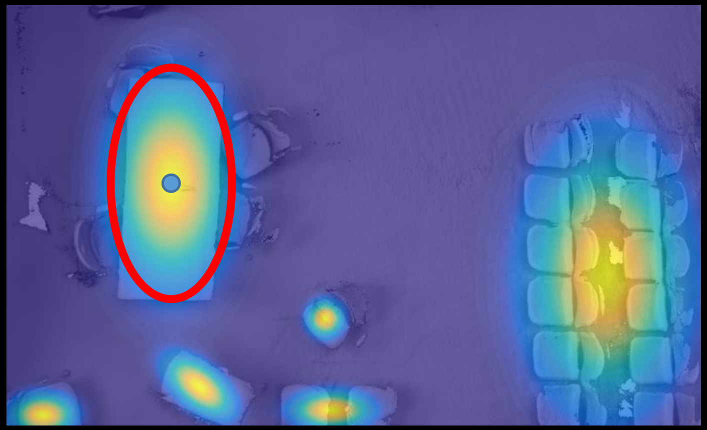




- Interior obstacle cost [Sun et al. 2016]

$$E^{int}(p) = \exp\left(-\frac{1}{2\sigma^2}\left(\frac{u'^2}{w^2} + \frac{v'^2}{h^2}\right)\right)$$

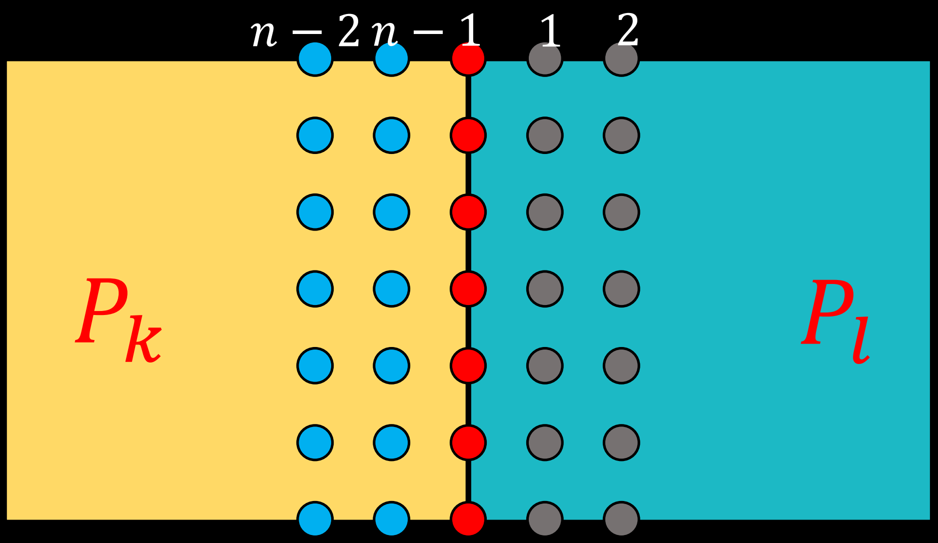
$$\begin{pmatrix} u' \\ v' \end{pmatrix} = \begin{pmatrix} u \\ v \end{pmatrix} \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} - \begin{pmatrix} u_c \\ v_c \end{pmatrix}$$



Constraints

- Smoothness constraints:

$$\boldsymbol{c}_{n,j}^{k} = \boldsymbol{c}_{0,j}^{l}$$
$$\boldsymbol{c}_{n,j}^{k} - \boldsymbol{c}_{n-1,j}^{k} = \boldsymbol{c}_{1,j}^{l} - \boldsymbol{c}_{0,j}^{l}$$
$$\boldsymbol{c}_{n,j}^{k} - 2\boldsymbol{c}_{n-1,j}^{k} + \boldsymbol{c}_{n-2,j}^{k} = \boldsymbol{c}_{2,j}^{l} - 2\boldsymbol{c}_{1,j}^{l} + \boldsymbol{c}_{0,j}^{l}$$



- Local bijection constraints:

$$\det J(p) > 0$$

✓ $J(p)$ is the Jacobian of the mapping at p

Formulation and optimization

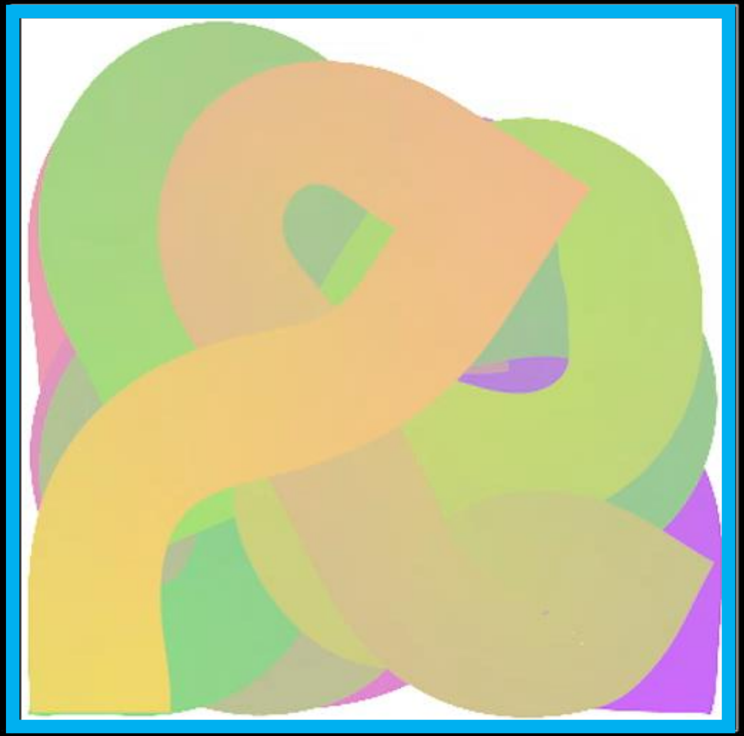
$$\min \text{distoriton cost} + \text{boundary cost}$$
$$\text{s.t. smoothness constraint}$$
$$\text{local bijection constraint}$$

✓ Optimization process

- Super-patch based assembly
- Newton’s method

Global optimization

- Perform a global optimization after all assemblies



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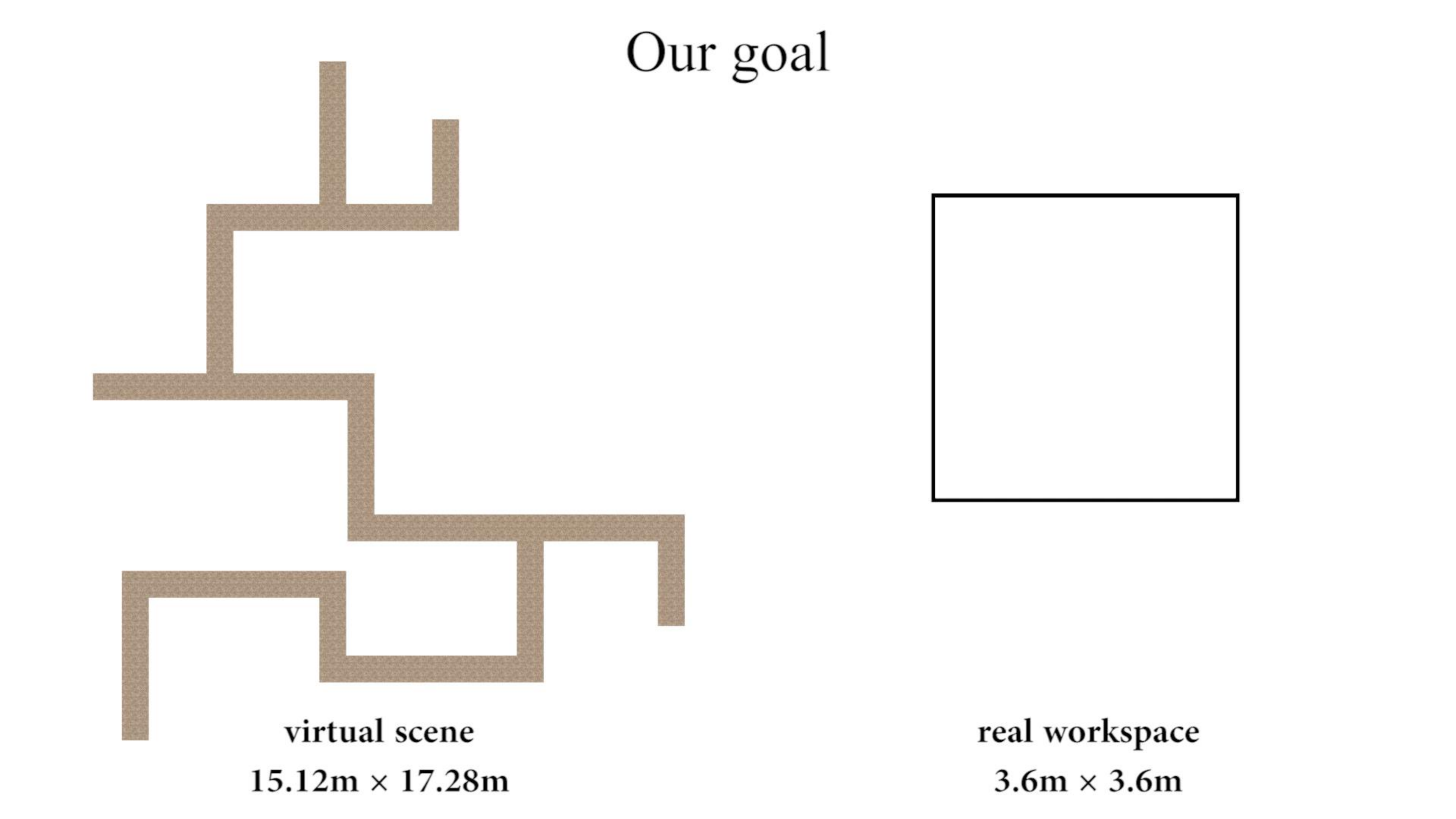
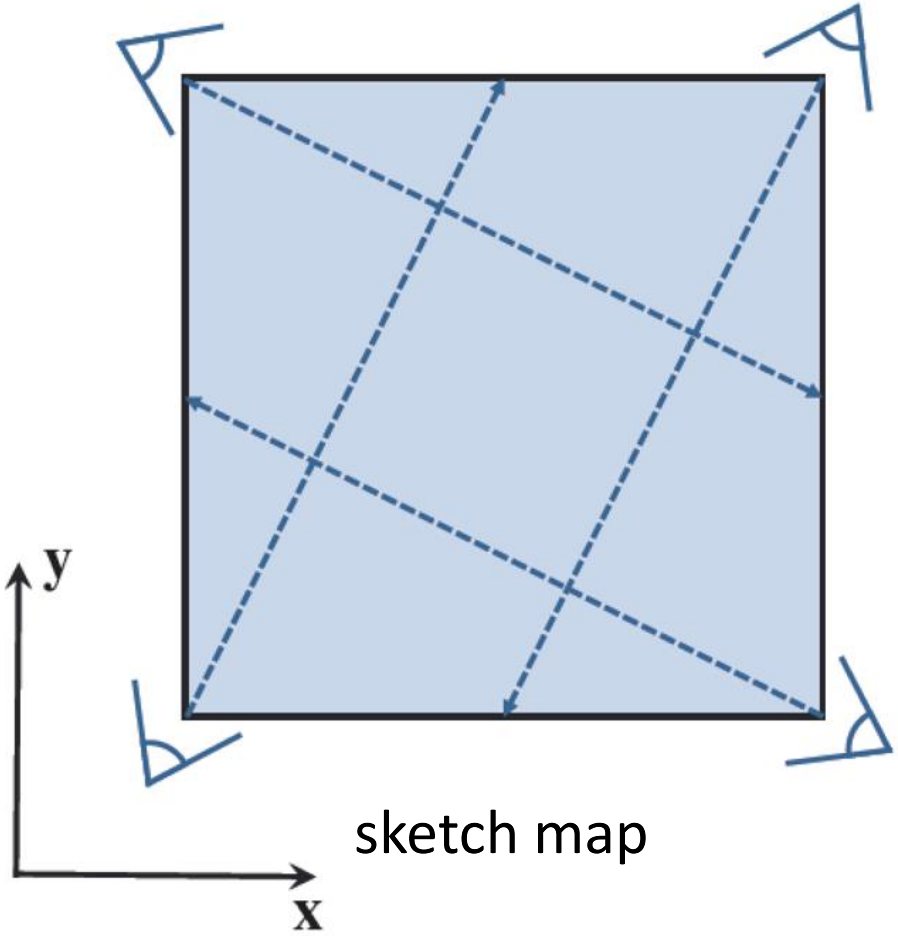
Recap: our SAM method



Experiments

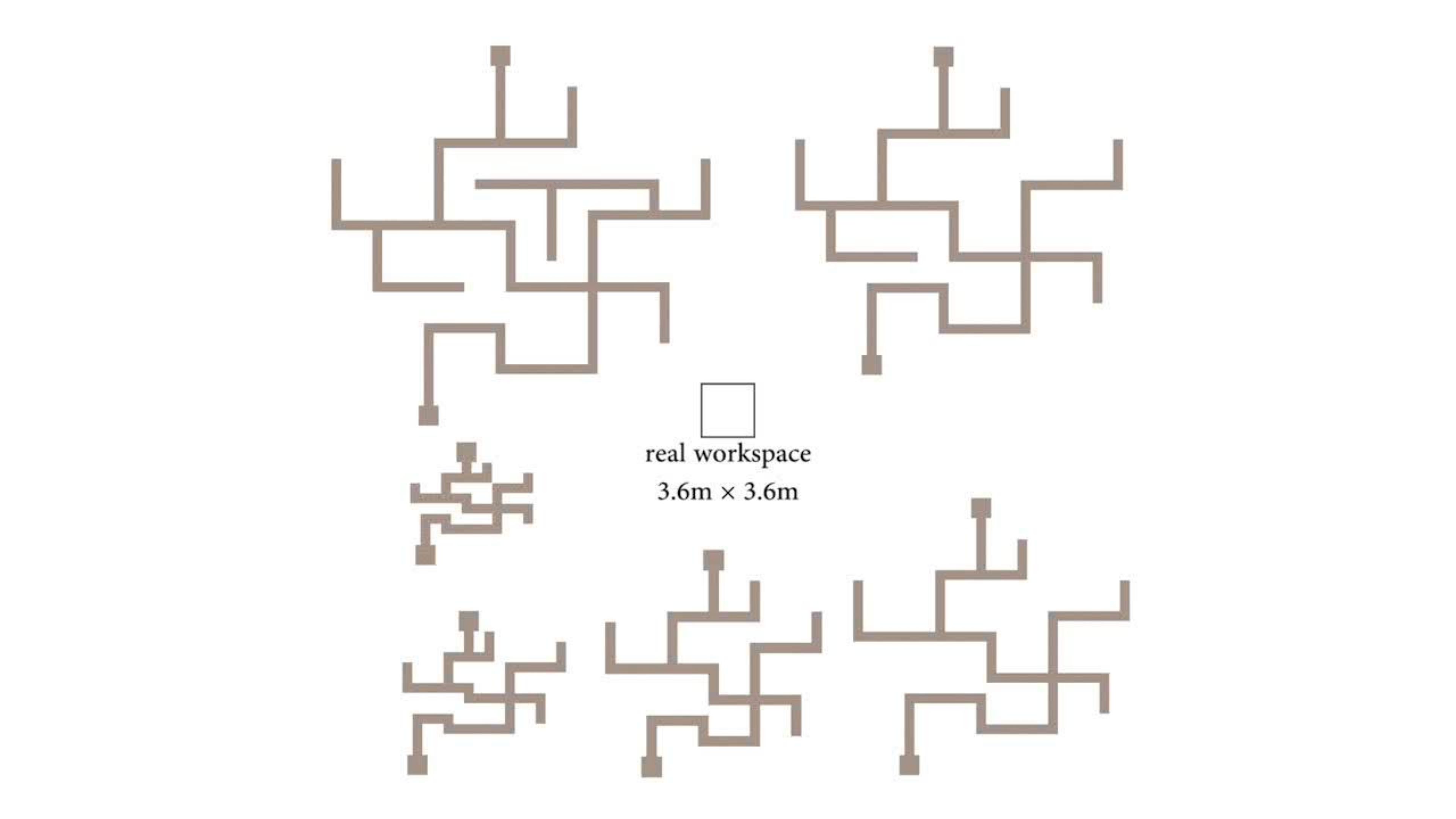
Setup



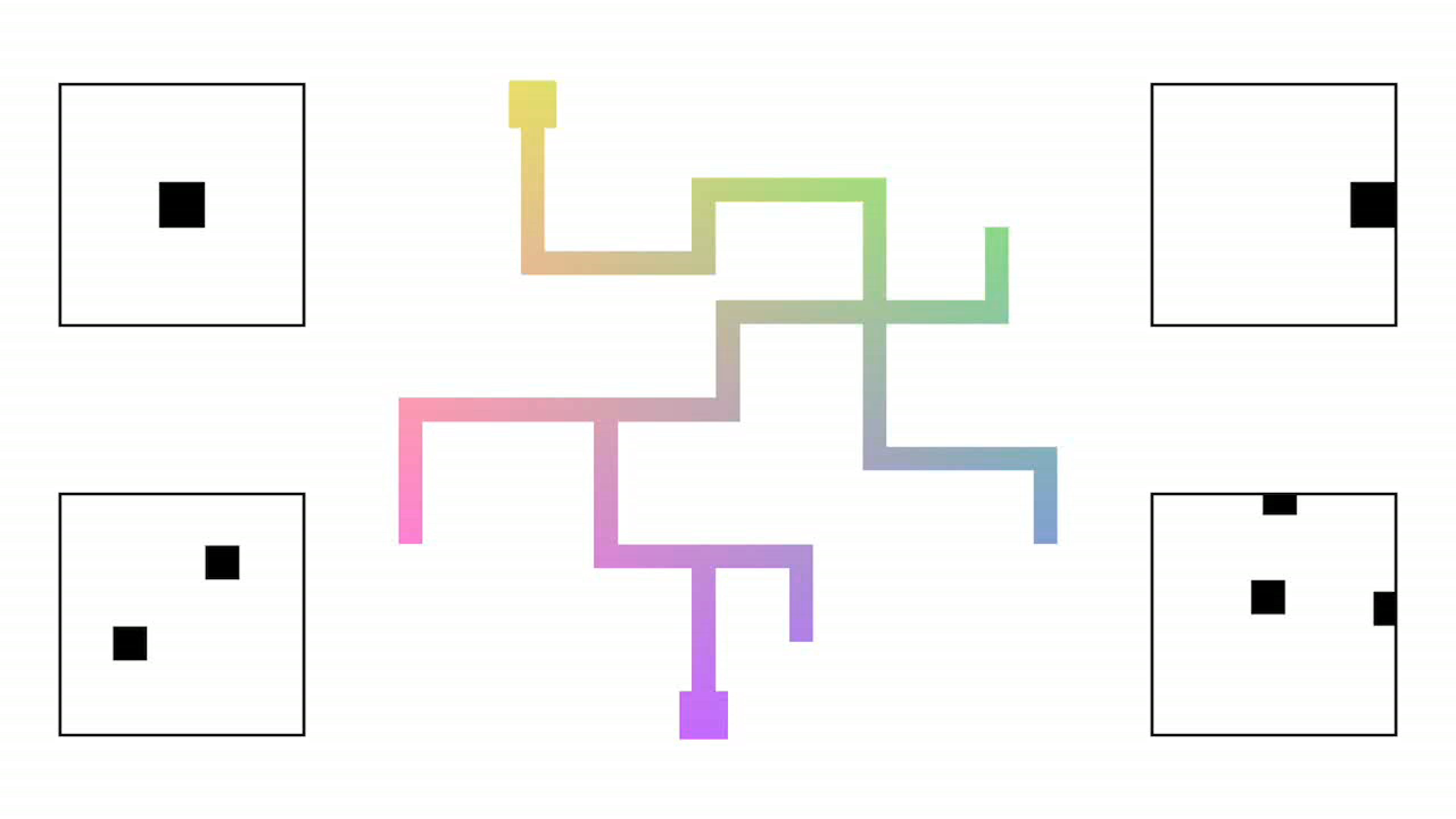
sketch map

real workspace

User studies: various virtual scenes

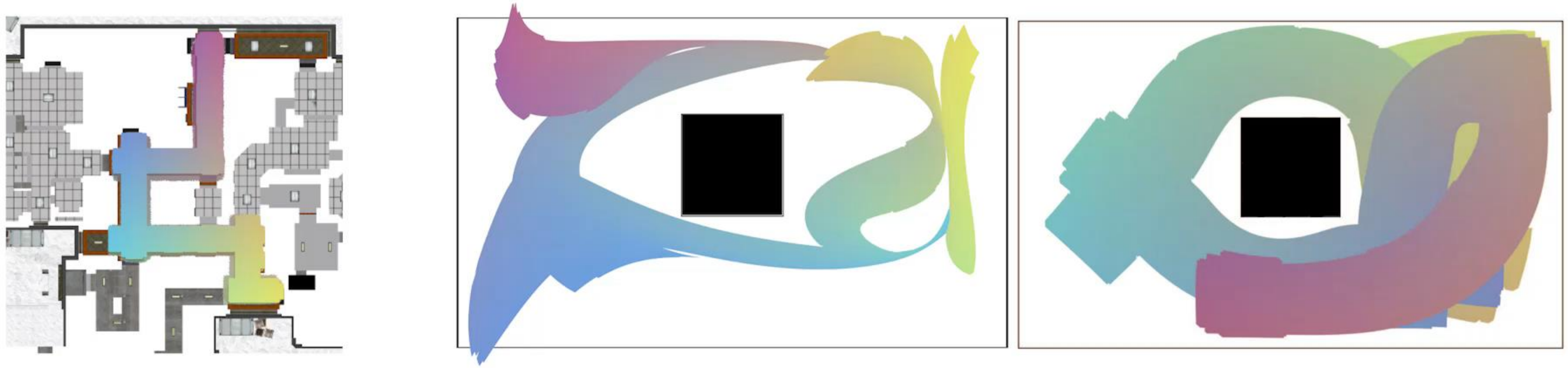


Interior obstacles



Comparison to [Sun et al. 2016]: simulation

Comparison to [Sun et al. 2016]



virtual environment 200 × 200

real workspace 60 × 100 + obstacle
$\delta^{iso}_{max} = 3.87 \times 10^4, \delta^{iso}_{avg} = 22.53$

real workspace 60 × 100 + obstacle
$\delta^{iso}_{max} = 1.95, \delta^{iso}_{avg} = 1.21$

Comparison to [Sun et al. 2016]: user study

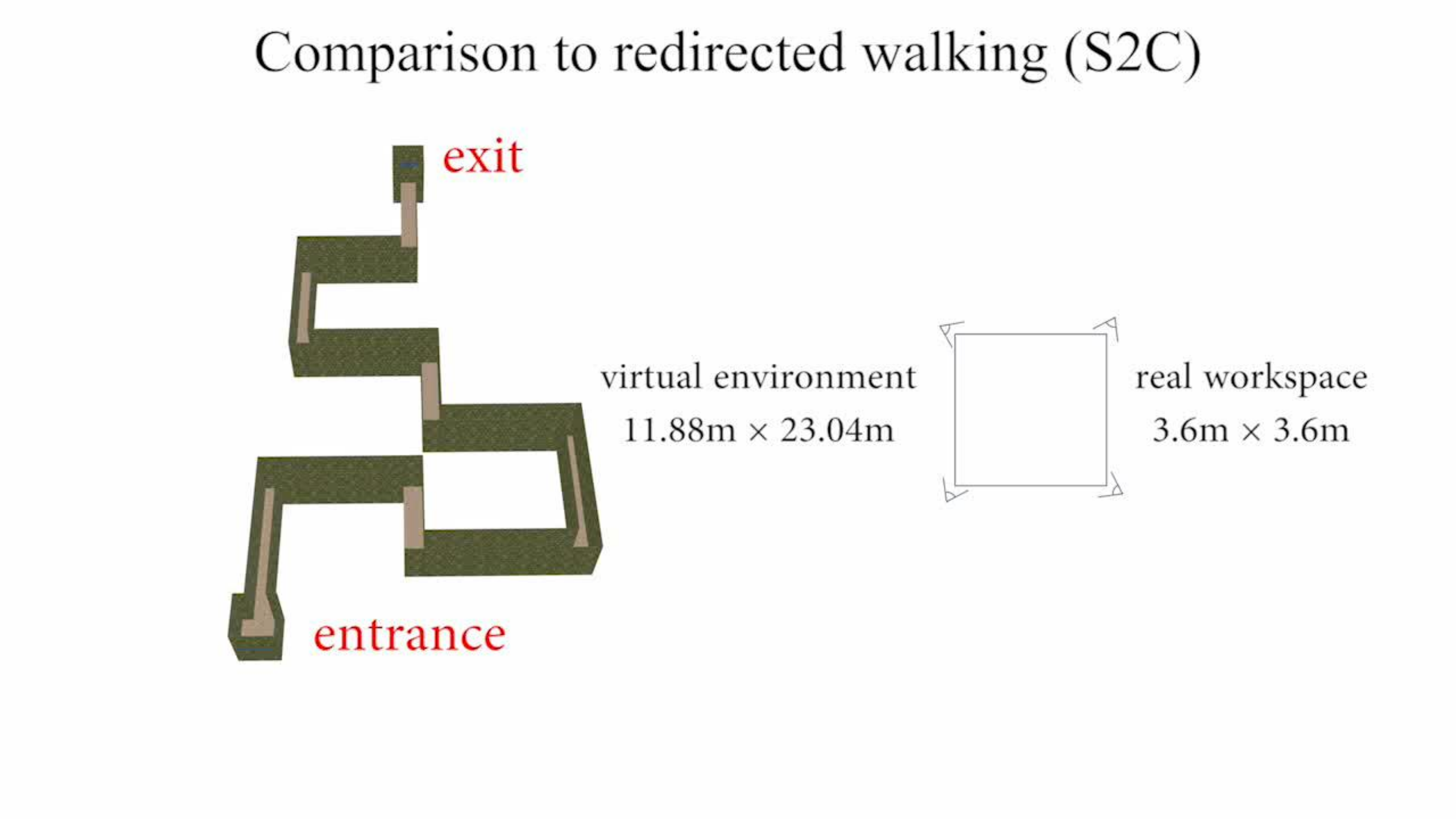
Comparison to [Sun et al. 2016]

virtual office environment
200×200

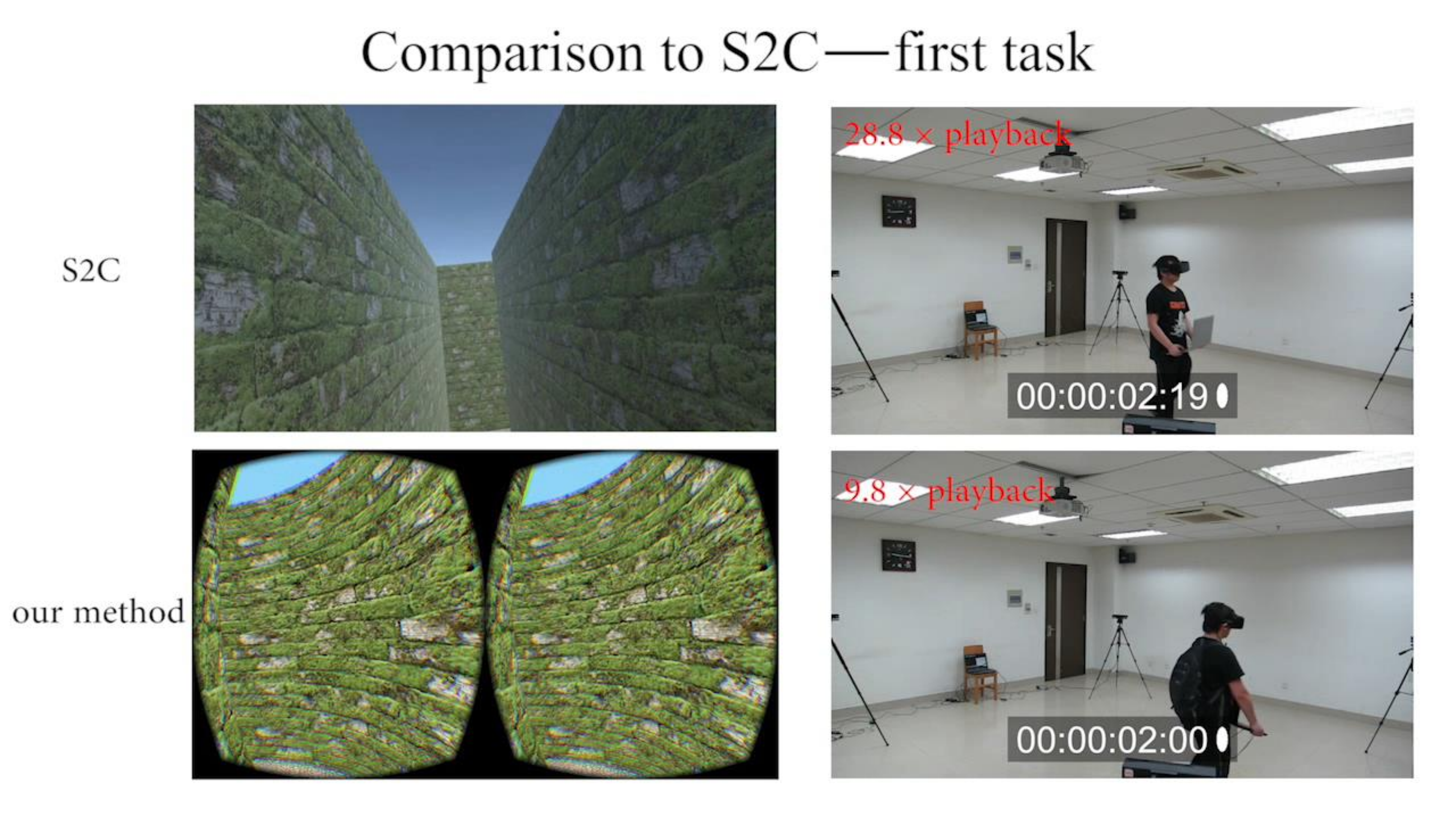
real workspace 70×70
[Sun et al. 2016]
$\delta^{iso}_{\max} = 550.71, \delta^{iso}_{\text{avg}} = 2.17$

real workspace 70×70
our method
$\delta^{iso}_{\max} = 1.95, \delta^{iso}_{\text{avg}} = 1.15$

Comparisons with redirected walking

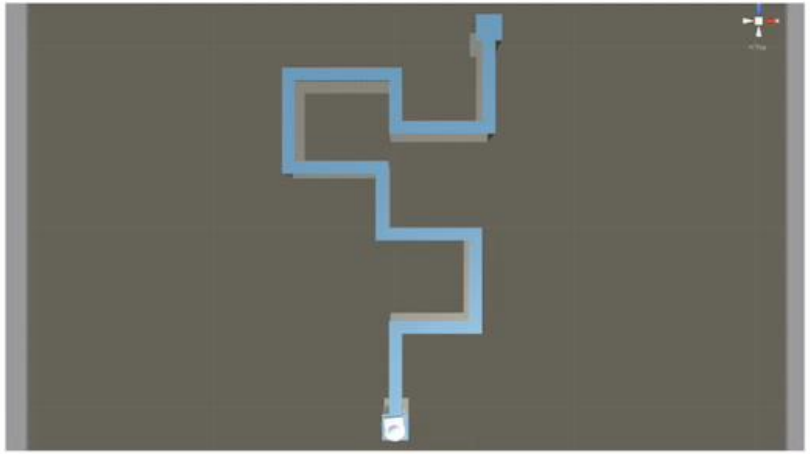


Comparisons with redirected walking



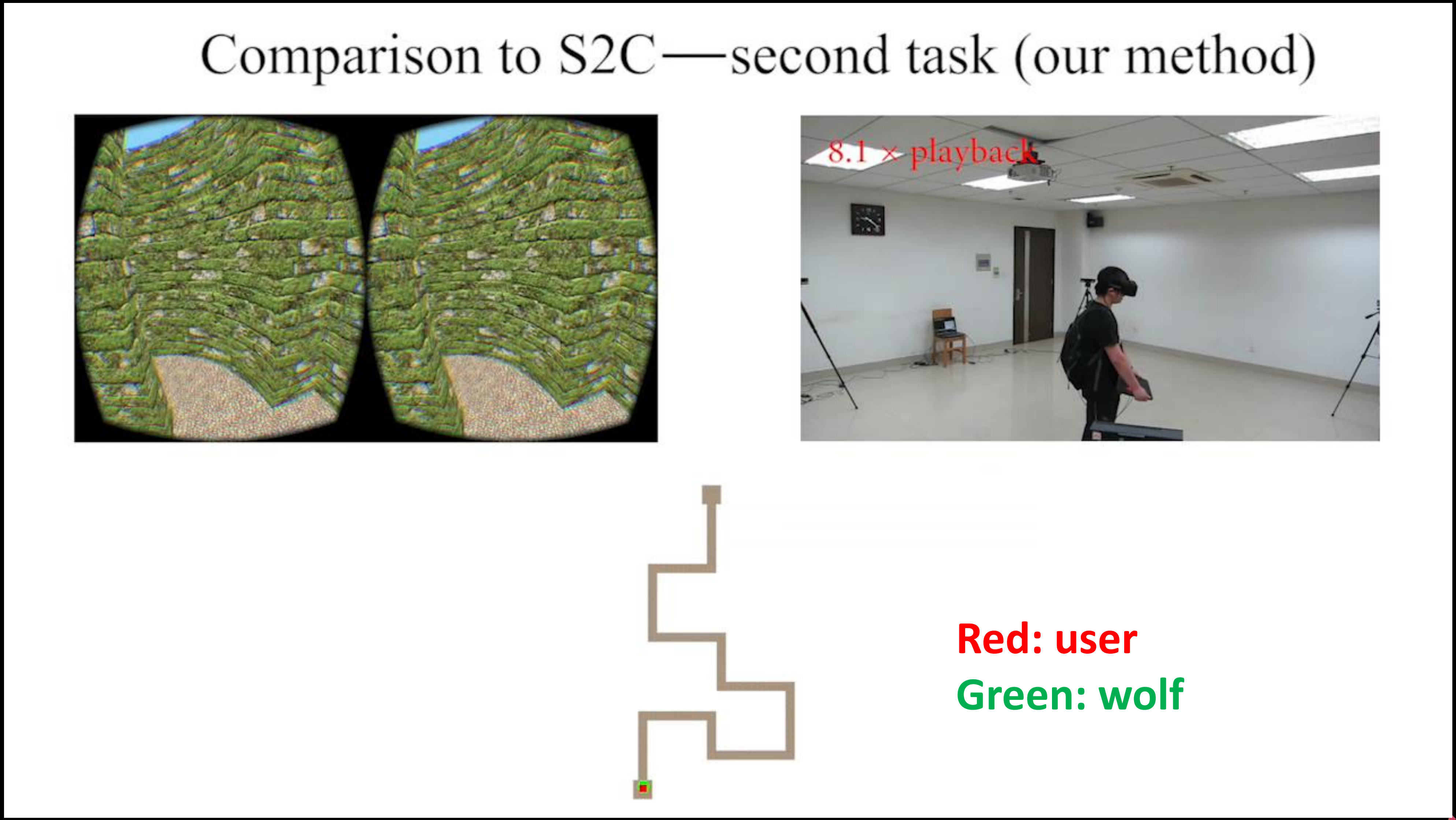
Comparisons with redirected walking

Comparison to S2C—second task (S2C)



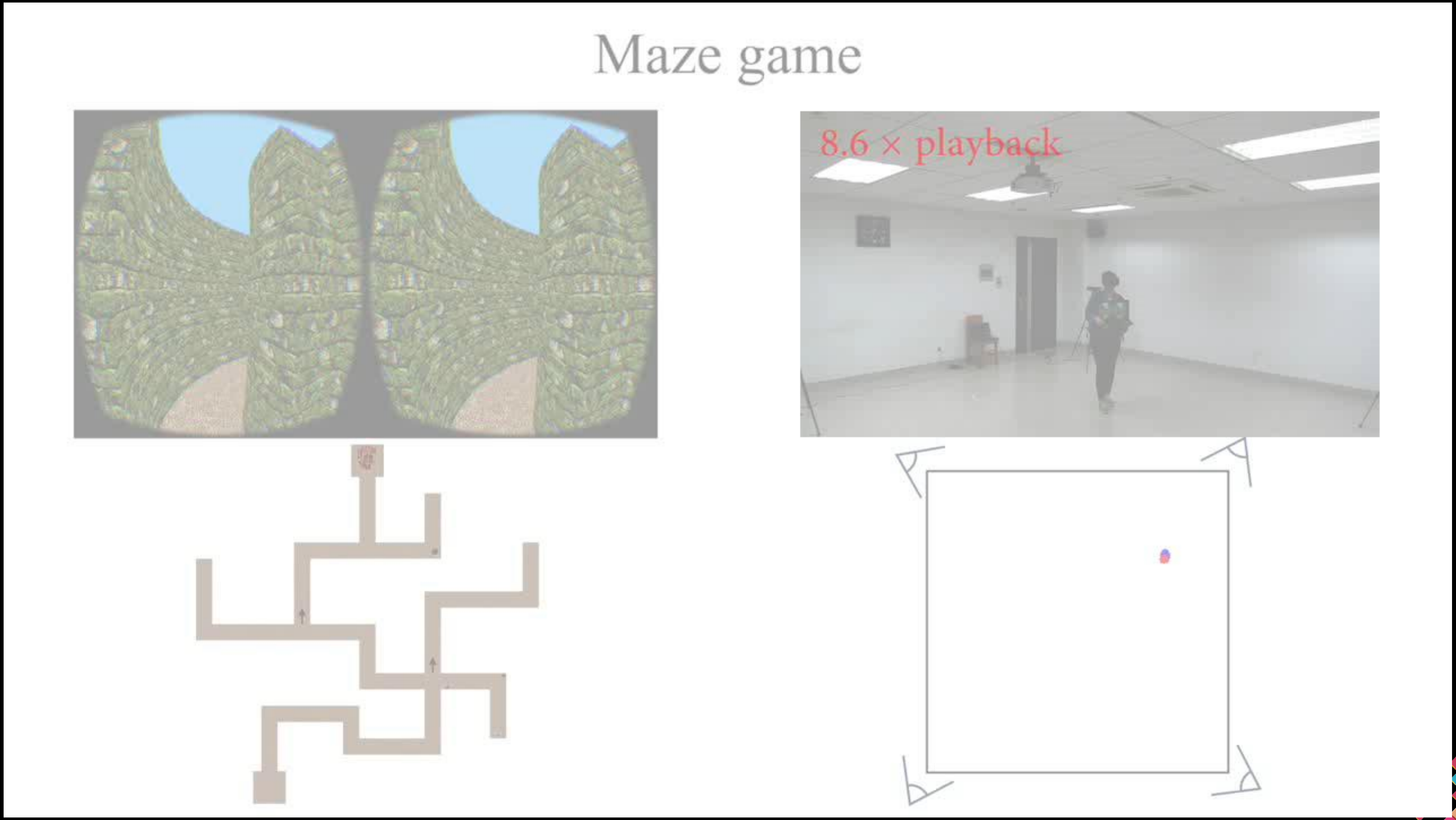
Square: user
Circle: wolf

Comparisons with redirected walking



Red: user
Green: wolf

Applications



Conclusion

- A novel **divide-and-conquer** method for mapping large-scale virtual scene into small real workspace
  - Much less distortion
  - Better walking experience
- Can work for any large virtual scenes

Conclusion

Limitations

- Pathways with large widths
- Only pathway-type scene

Future work

- Open scenes
- Mapping scenes in AR

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Acknowledgements

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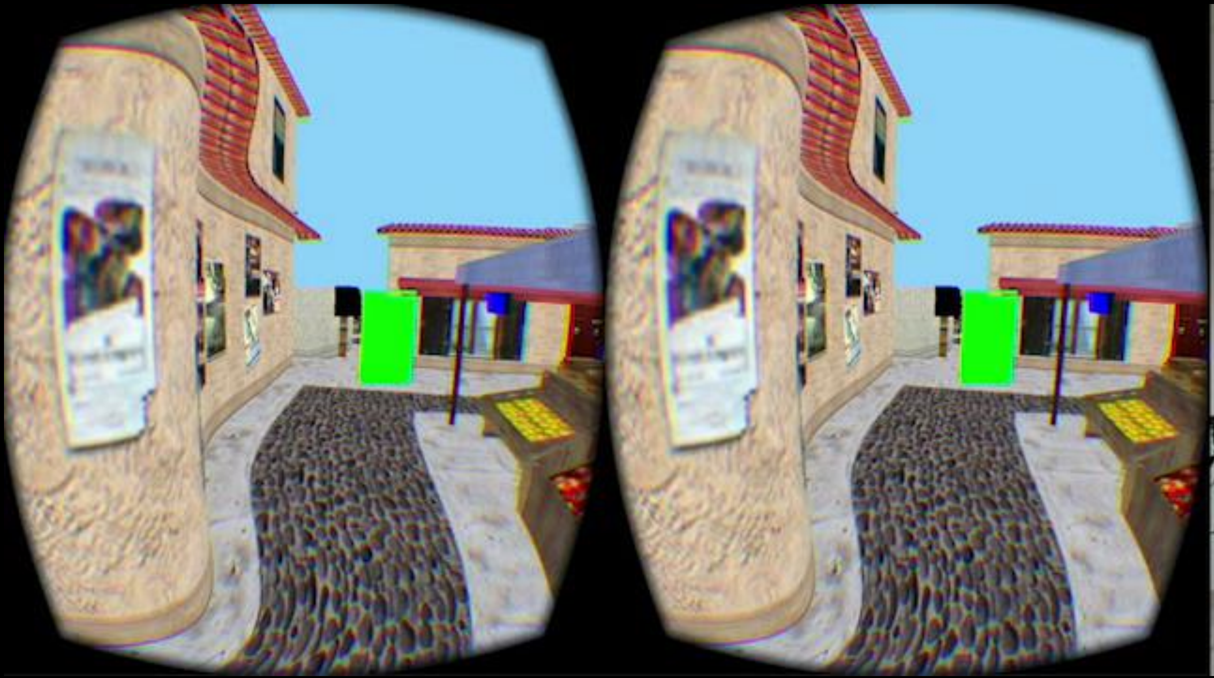
- Qi Sun ([Sun et al. 2016]), Stony Brook University
- Mahdi Azmandian ([Azmandian et al. 2016]), University of Southern California
- Peng Song, Xuejin Chen, University of Science and Technology of China



Thank you!

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