A Conformal Mapping-based Framework for Robot-to-Robot and Sim-to-Real Transfer Learning

Shijie Gao[1], Nicola Bezzo[1]

[1] Electrical and Computer Engineering
University of Virginia

IEEE/RSJ International Conference on Intelligent Robots and Systems
IROS 2021

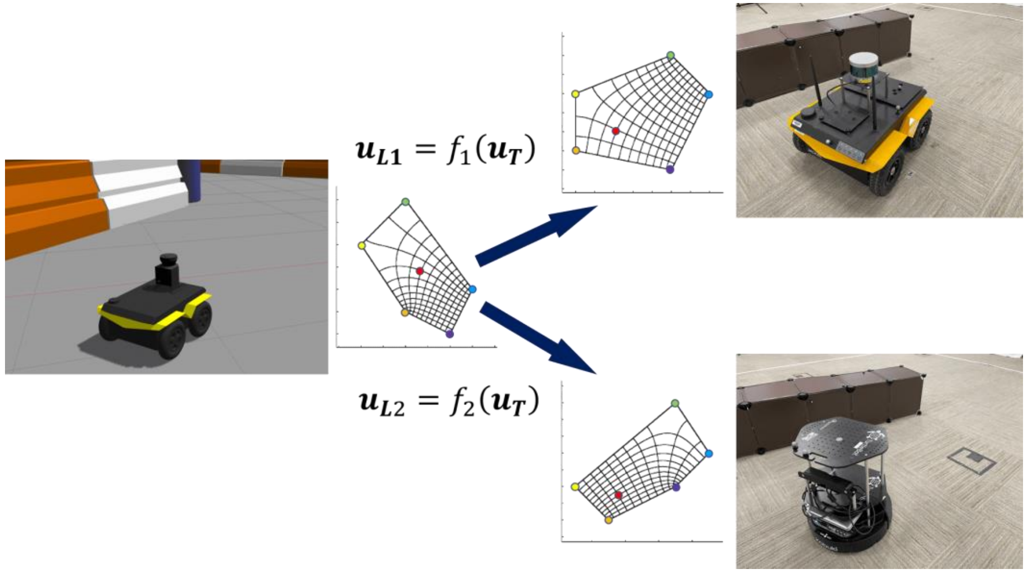
UVA ENGINEERING
LINK LAB

AMR LAB

Introduction

Motivations:

- Planning and control methods developed in Simulations can **behave differently** on real systems.
- The algorithm designed specifically for one platform is **hard to be transferred** to other systems.
- The same system needs to be adjusted **over time** or under **different environments**.



Goals:

- Reduce the sim-to-real gap to **boost** the deployment of **motion planning** and **control methods**.
- **Transfer knowledge** designed for a specific robot onto a different robot.
- Quickly learn the limits and proper input mapping to **compensate** for system **deterioration**.

Problem Definition

1. Teacher-Learner Control Transfer:

- Given a teacher robot **with dynamics** $\boldsymbol{x_T(t+1)=f_T(x_T(t),u_T(t))}$ and **control law**.
- Given a learner robot **without** knowing its **dynamics** f_L.
- Find a policy g to map the input from teacher to the learner, such that,

$$\boldsymbol{u}_L(\boldsymbol{t}) = g(\boldsymbol{u}_T(\boldsymbol{t}))$$

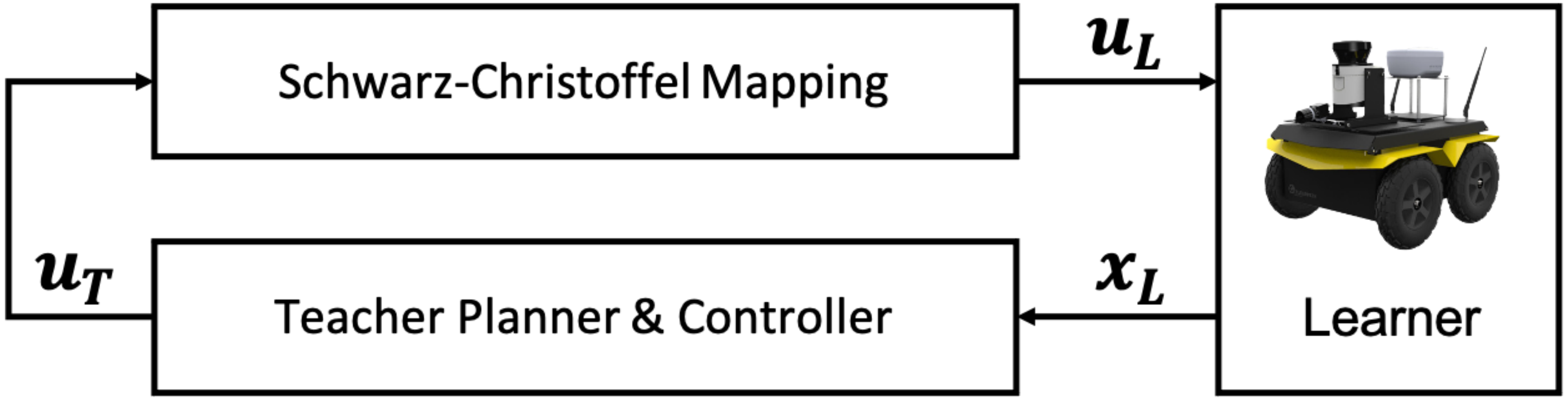
$$\boldsymbol{f}_T\big(\boldsymbol{x}_T(\boldsymbol{t}),\boldsymbol{u}_T(\boldsymbol{t})\big) = \boldsymbol{f}_L(\boldsymbol{x}_L(\boldsymbol{t}),\boldsymbol{u}_L(\boldsymbol{t}))$$

2. Teacher-Learner Motion Planning Adaptation

- Assume that the learner has less capability than the teacher
- Design a teacher's planning policy π_T^L such that the computed trajectory **adapts to** the **limitation** of the learner

Methodology

- **Schwarz-Christoffel mapping (SCM)** based command mapping from the teacher's command domain to the learners.
- **Motion Primitive** based path planning limits the trajectory within the learner's capability.



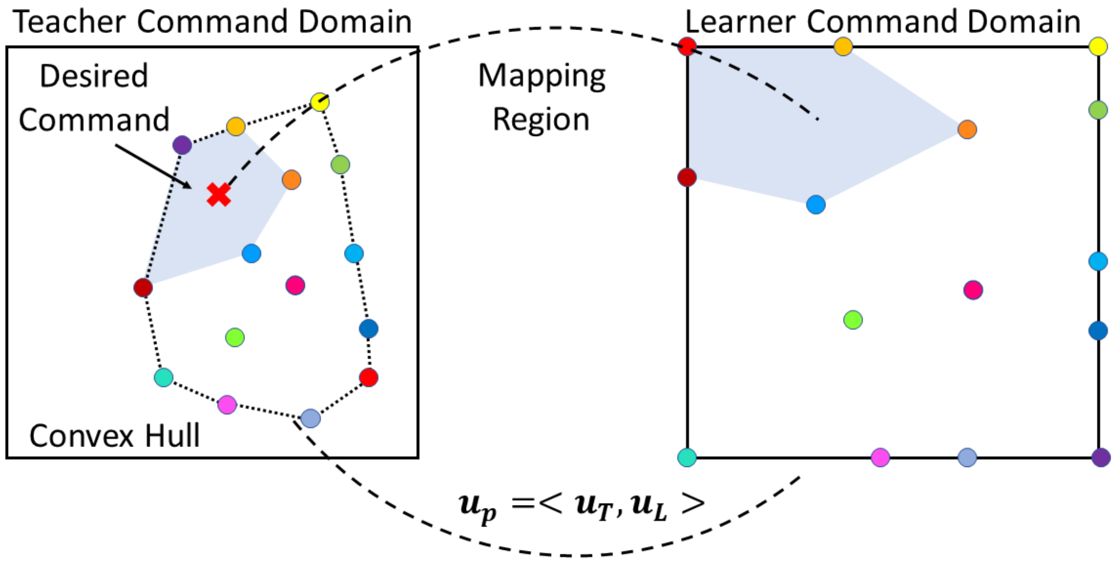
Methodology: Schwarz-Christoffel Mapping

Command Pair

- A pair of commands which makes the two vehicles produce the **same motion**.

Area of Interest

- Given a desired teacher command, the **neighboring commands pairs** construct areas of interest for mapping on both sides.



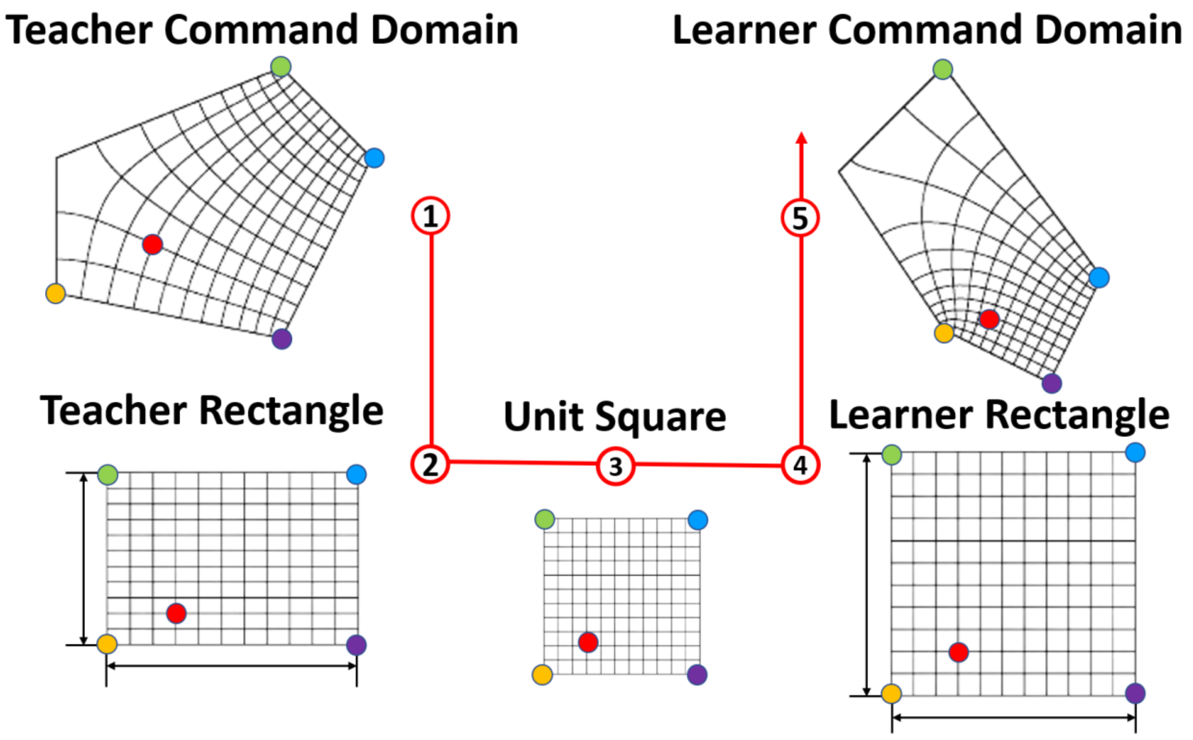
Methodology: Schwarz-Christoffel Mapping

Mapping from the teacher command domain to the learner's

- On each side, SCM maps the area of interest to a rectangle of a unique aspect ratio.
- A unit square is used to bridge the two rectangles.

Mapping from a polygon to a rectangle

- Consider the polygon as a generalized quadrilateral.
- Pick 4 vertices as the vertices for the quadrilateral.



Methodology: Schwarz-Christoffel Mapping

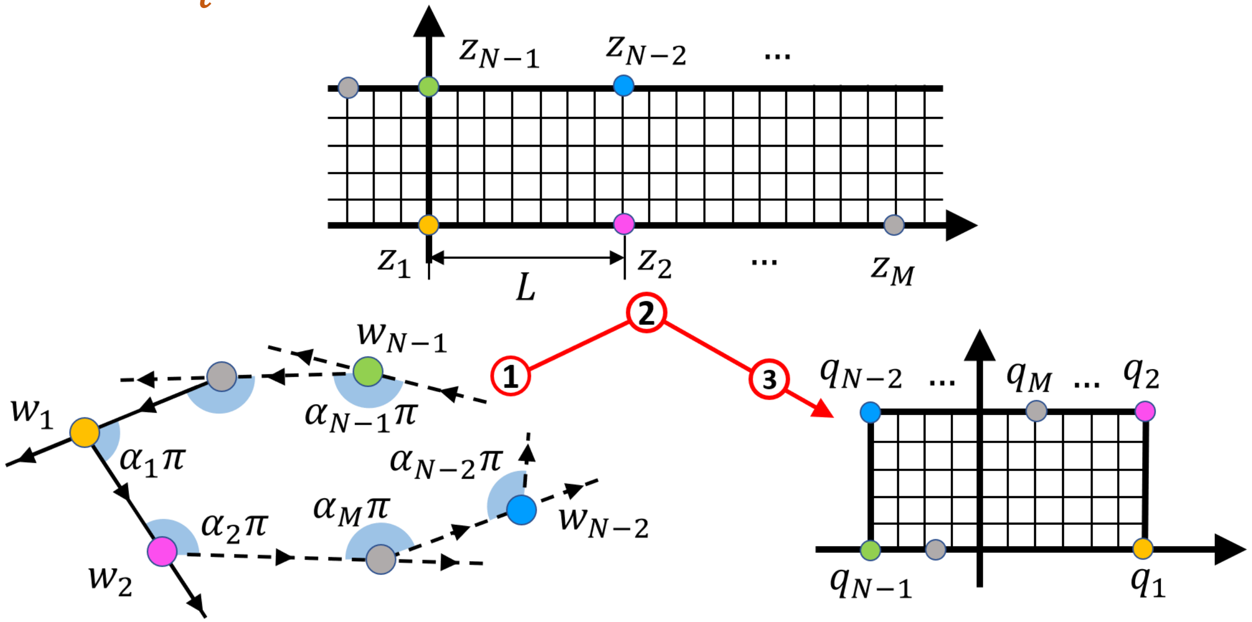
1. Mapping from polygon to bi-infinite strip

- Order the polygon vertices w_i and the pre-vertices z_i in **ccw**.
- From strip to the generalized quadrilateral.

$$w = f_{\mathbb{S}}^{\Gamma}(z) = A \int_0^z \prod_{j=0}^{N} f_j(z)dz$$

- The angles $\alpha_i\pi$ are preserved by

$$f_j(z)=\begin{cases} e^{\frac{1}{2}(\theta_+-\theta_-)z} & j=0, \\ \{-i\cdot\sinh[\frac{\pi}{2}(z-z_j)]\}^{\alpha_j} & 1\leq j\leq M, \\ \{-i\cdot\sinh[-\frac{\pi}{2}(z-z_j)]\}^{\alpha_j} & M+1\leq j\leq N. \end{cases}$$



- Fixing $z_1 = 0$ to remove constant C.
- The location of the rest of the pre-vertices z_i

$$\frac{w_{k+1}-w_k}{w_2-w_1}=\frac{\int_{z_k}^{z_{k+1}}\prod_{j=0}^{N} f_j(z)dz}{\int_{z_1}^{z_2}\prod_{j=0}^{N} f_j(z)dz},\ k=2,3,\ldots,N-2$$

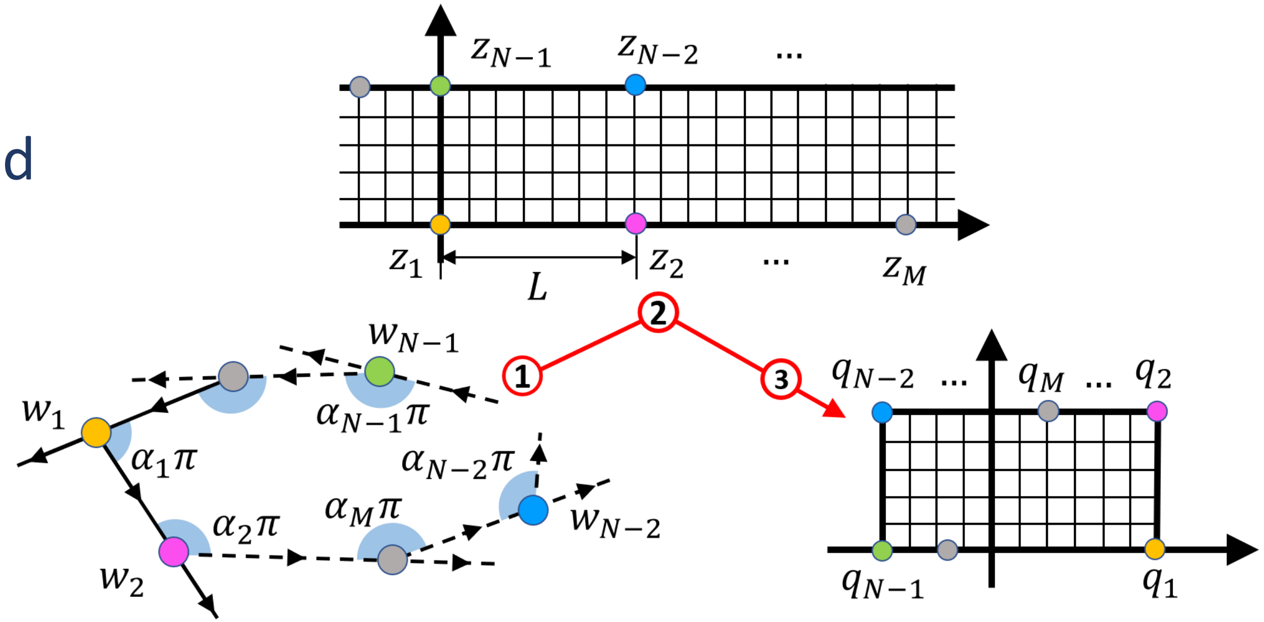
Methodology: Schwarz-Christoffel Mapping

2. Mapping from rectangle to bi-infinite strip

- Leveraging the Jacobi elliptic of the first kind

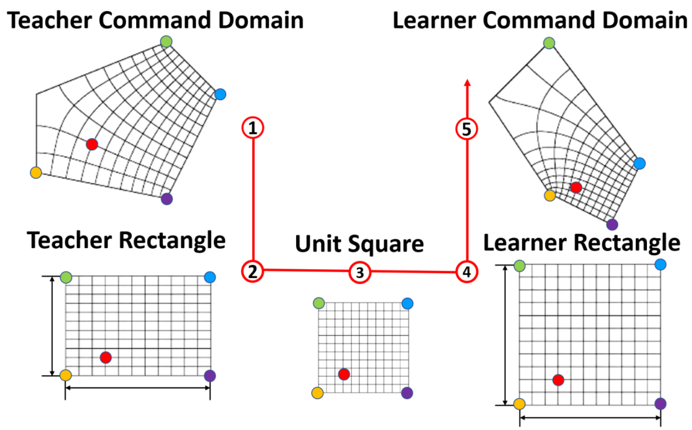
$$z = f_{\mathbb{Q}}^{\mathbb{S}}(q) = \frac{1}{\pi} \cdot \ln(\sin(q|m))$$

- The shape of the rectangle is linked to L



The mapping function from polygon to the rectangle

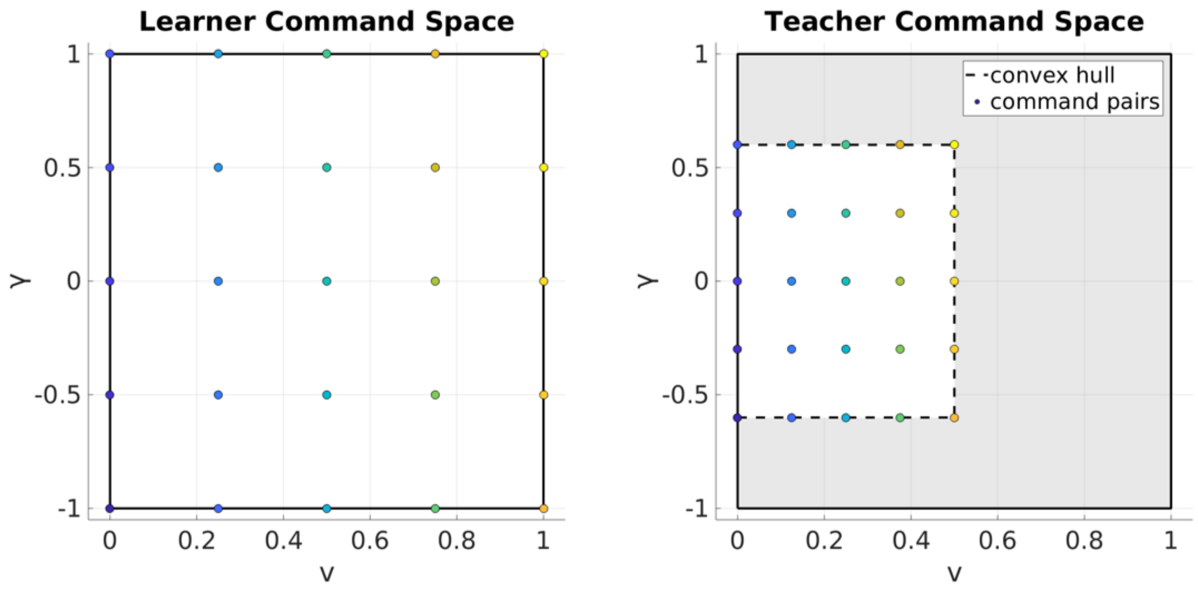
$$q = f_{SCM}(w) = f_{\mathbb{Q}}^{\mathbb{S}^{-1}}(f_{\mathbb{S}}^{\Gamma^{-1}}(w))$$



Methodology: Primitive Path Planning

Learn the learner's limitations:

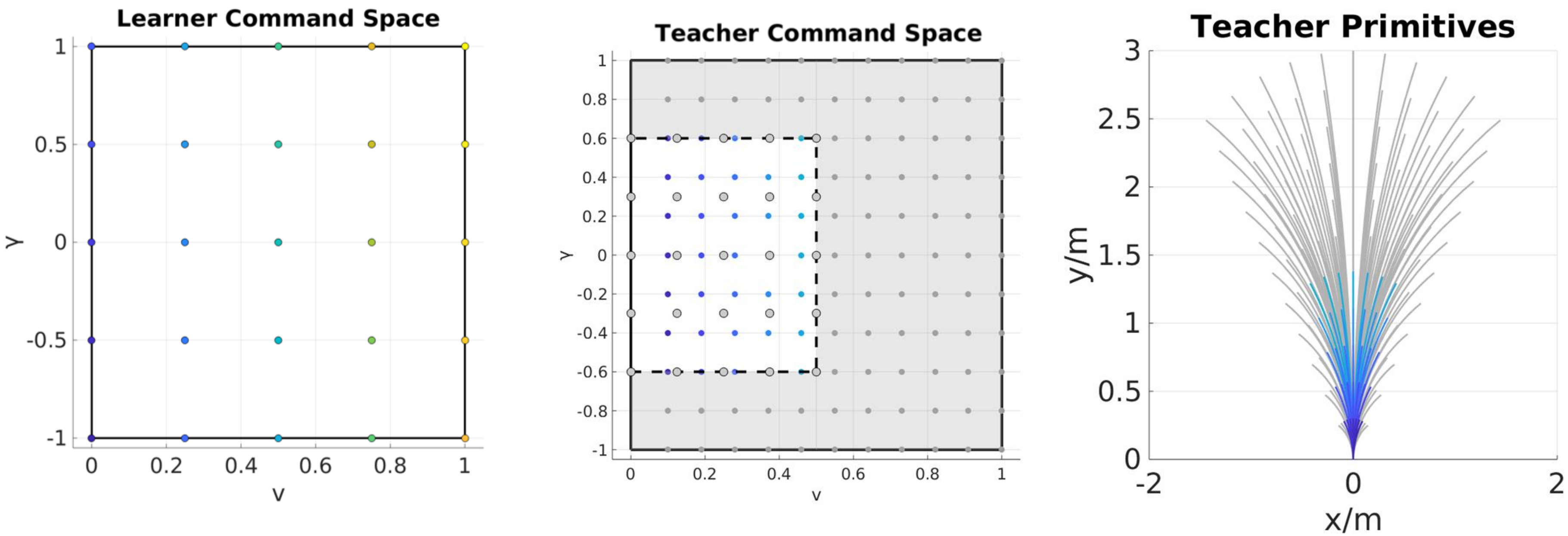
- The learner's limitation is characterized on the teacher command space by the convex hull built by the command pairs.
- The convex hull does not need to cover the whole command space of the learner



Methodology: Primitive Path Planning

Motion primitives

- A teacher motion primitive is built by feeding the teacher a sequence of the same command.
- The primitive whose associated command is in the convex hull is used for motion planning.



Methodology: Primitive Path Planning

Path planning

- The teacher compares the available **motion primitives** with the **corresponding segment** of the desired path to find the optimal local motion plan.

Evaluate metrics:

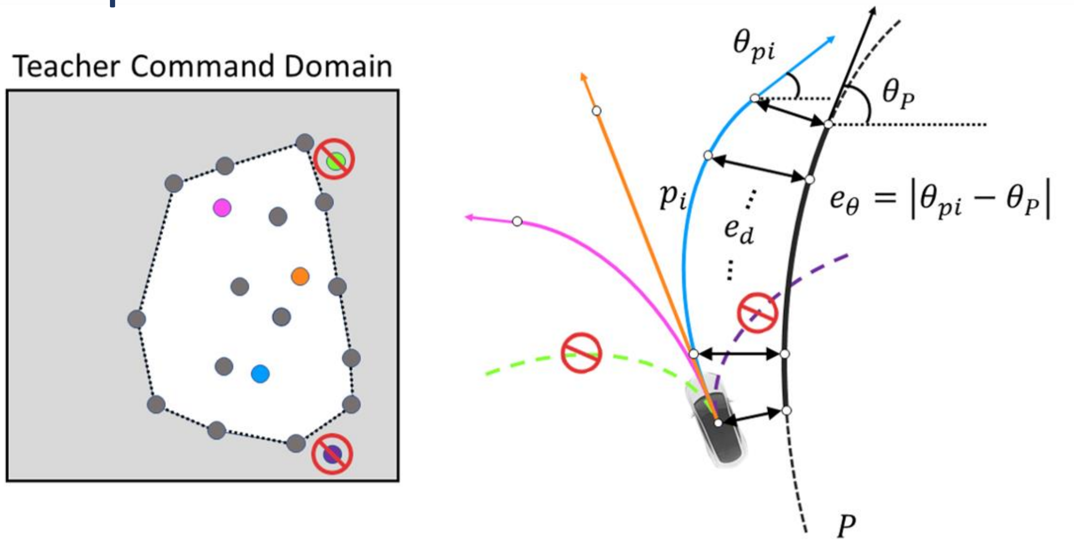
- dynamic time warping (DTW) distance

- heading difference

$$\delta_i = k_d \cdot e_d + k_\theta \cdot e_\theta$$

$$= k_d \cdot DTW(P, p_i) + k_\theta \cdot |(\theta_P - \theta_{p_i})|$$

$$p_i^* = \min_{p_1,\ldots,p_i} \delta_i.$$



An example of picking the optimal local motion

- The associated teacher **command of** the selected **motion primitive** will be the desired command and **mapped to the learner**.

Methodology: Primitive Path Planning

Event triggered replanning for safety monitor

- The amount of deviation $d_{\hat{e}}$ is monitored at runtime

– In **open area** :

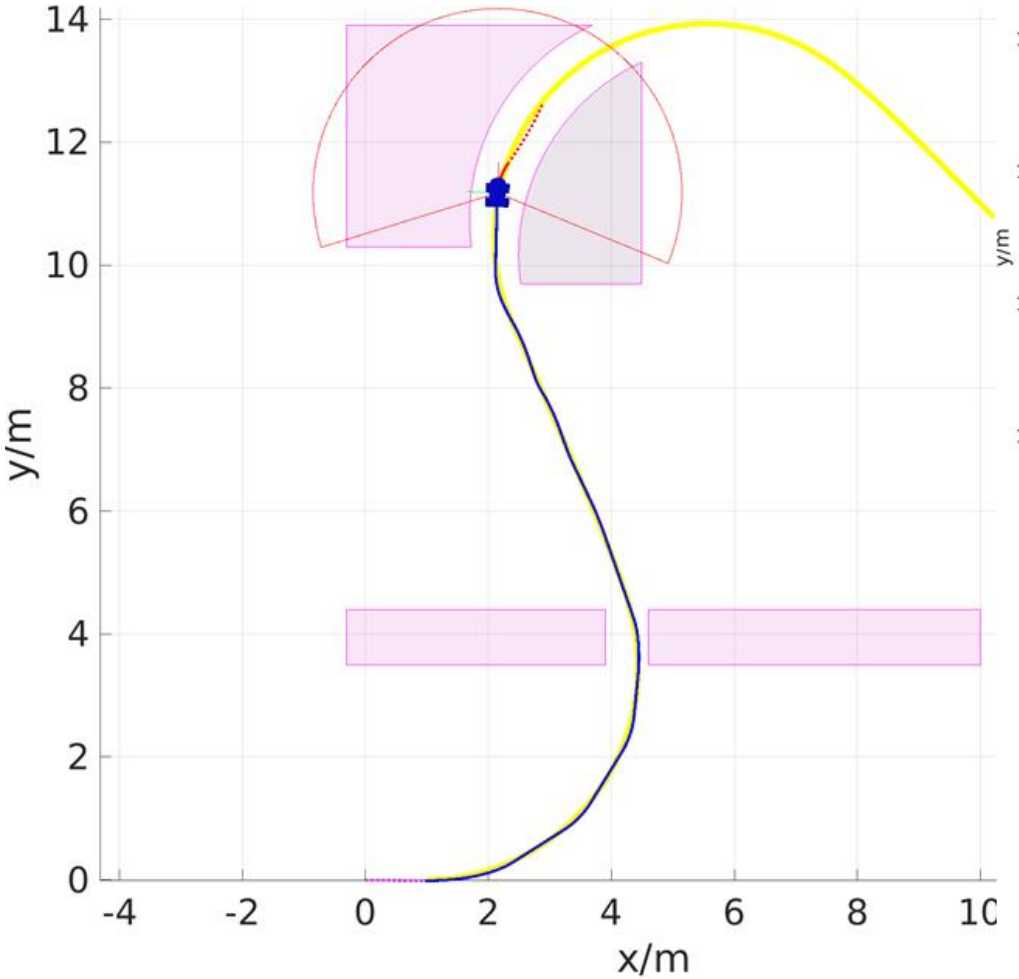
The deviation is allowed to be **large**.

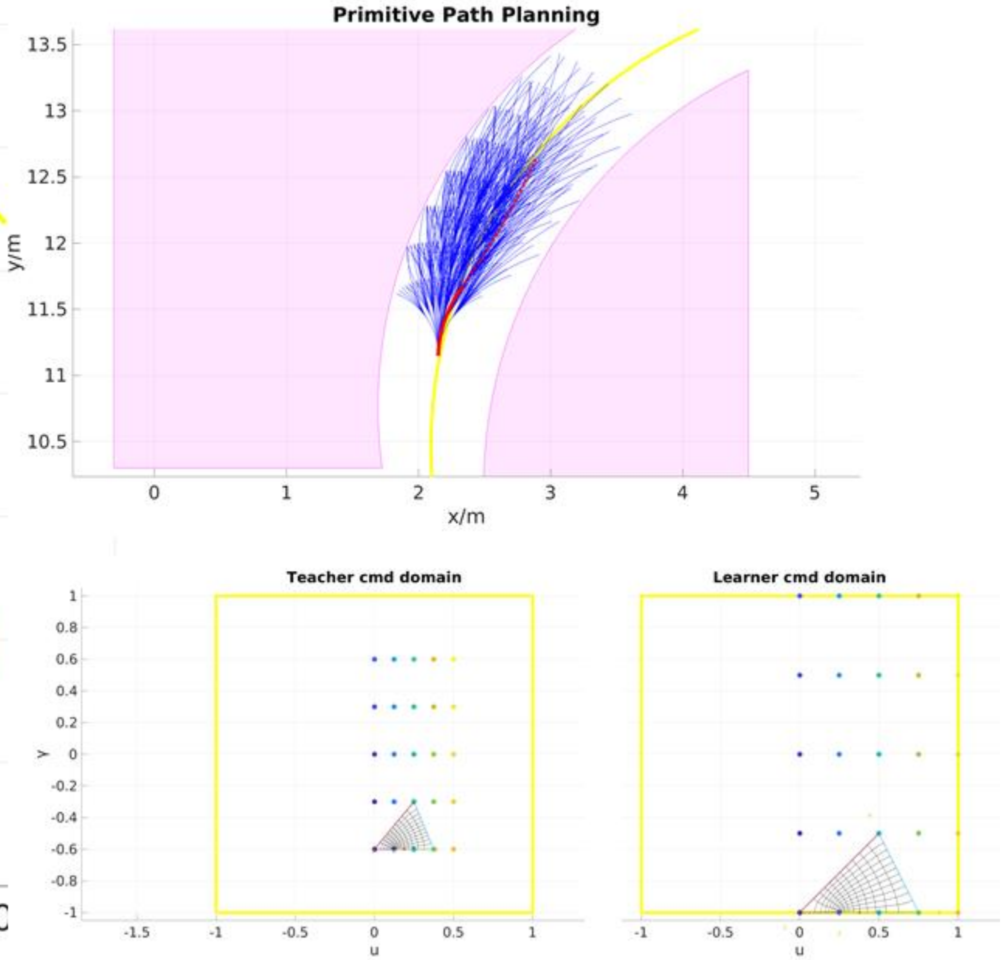
– In **cluttered** environment :

Even a **small deviation** should trigger the **replanning** for safety.

$$\epsilon = \begin{cases} \eta * \min(||p - o_i||) & i = 1, 2, \ldots, N_o \\ \infty & i = \varnothing, \end{cases}$$

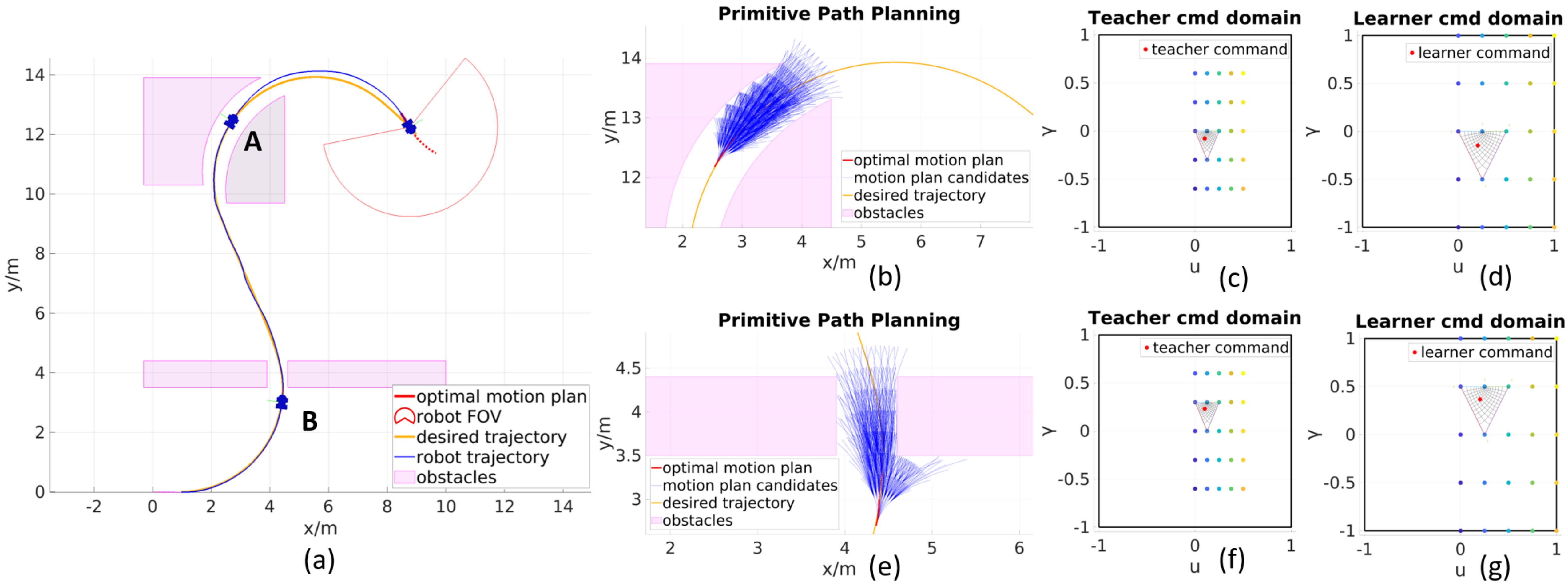
Simulation Results 1: Original System to Degraded System





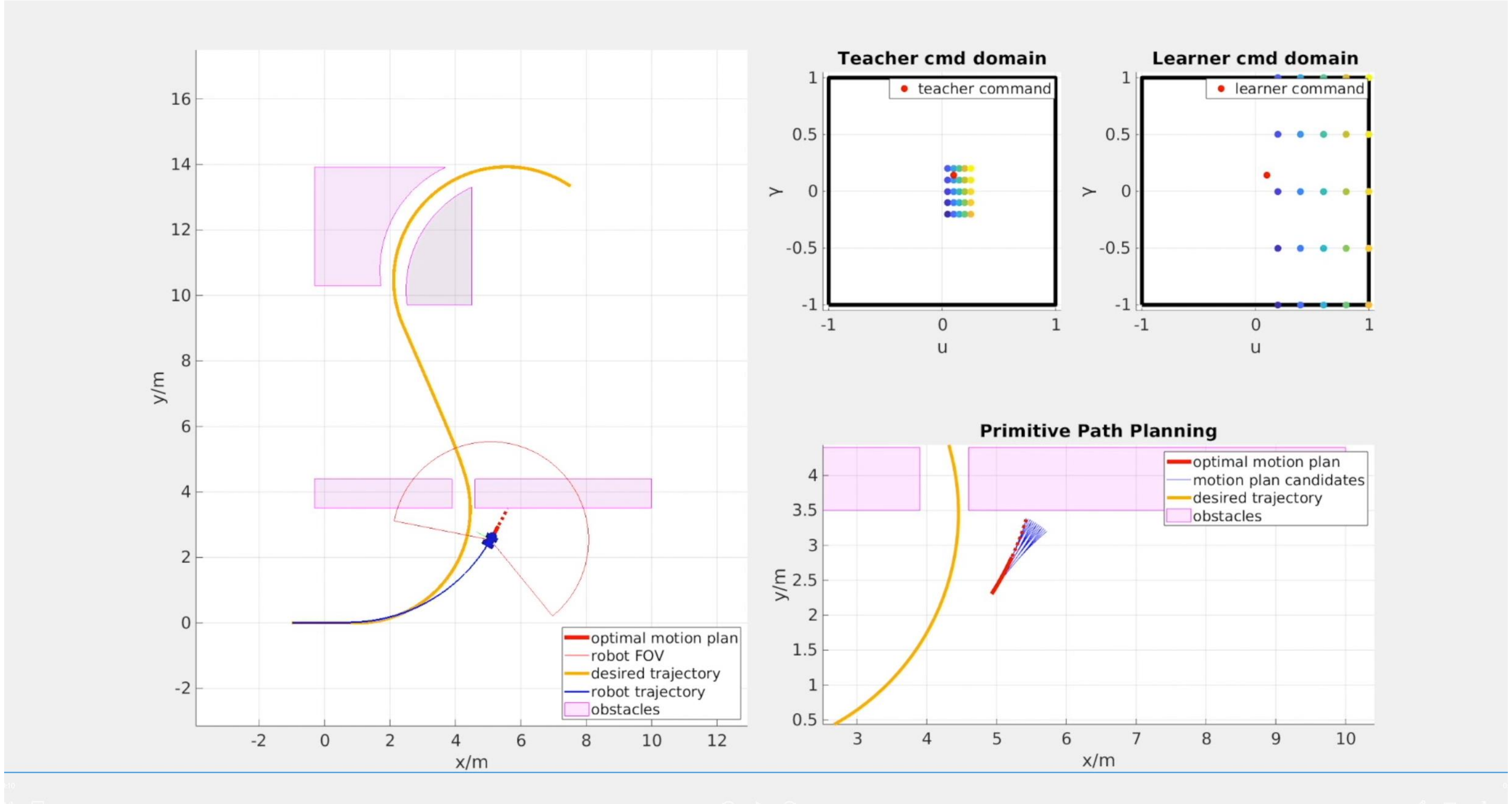
Simulation Results 1: Original System to Degraded System

- **With** the proposed approach



Simulation Results 2: Original System to Degraded System

- **Without** the proposed approach

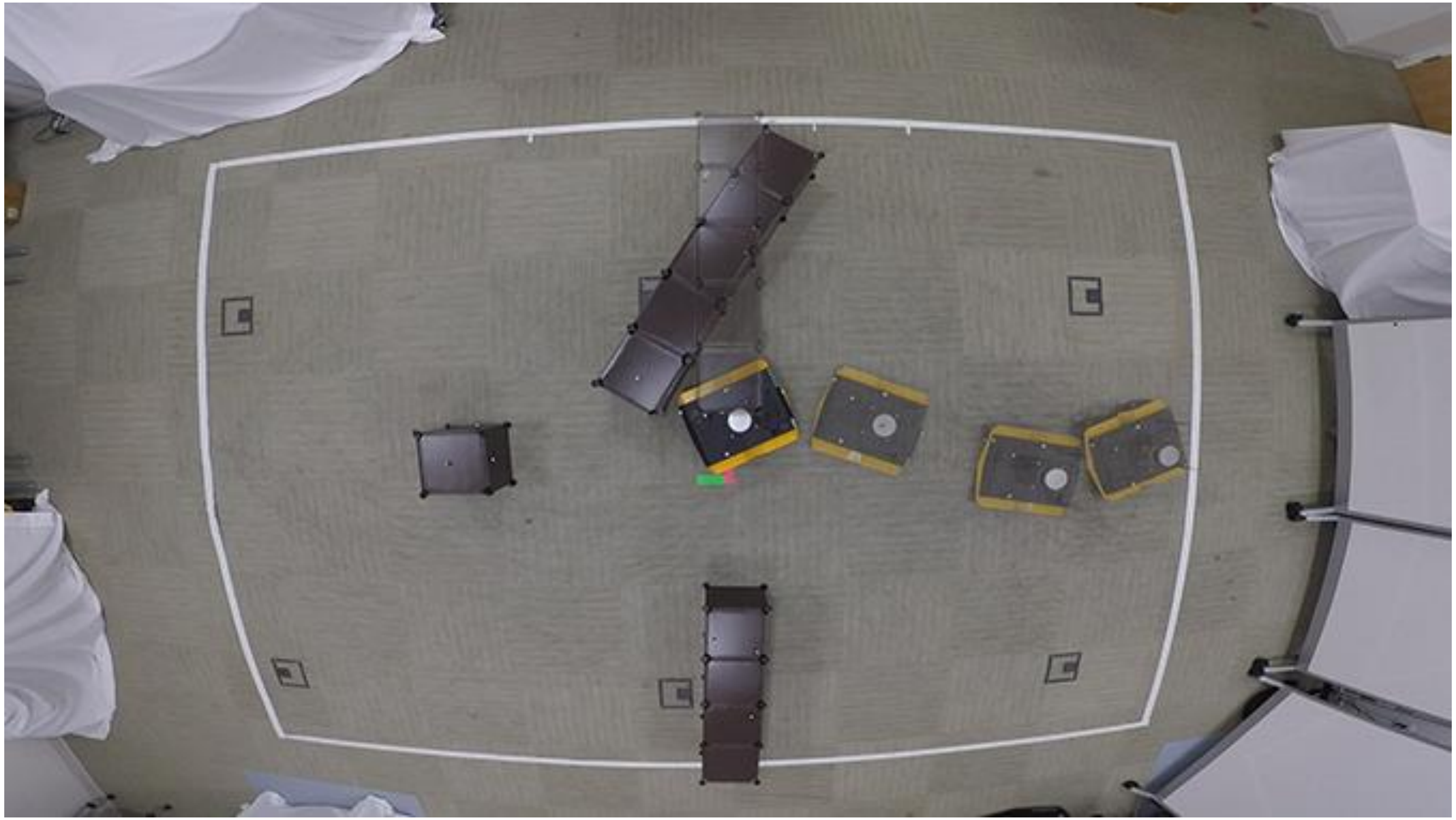


Experiment Results 1: Simulated UGV to Jackal UGV

- **With** the proposed approach

Experiment Results 2: Simulated UGV to Jackal UGV

- **Without** the proposed approach



Experiment Results 3: Simulated UGV to Turtlebot2 UGV

- **With** the proposed approach

Conclusions and Future Work

Summary:

- A novel ***light-weight*** transfer learning framework based on conformal mapping.
- Directly maps the control input while the learner's dynamics remain unknown.
- A motion planning policy that adapts to the learner's dynamics.

Current and Future Work:

- Transfer from a ***higher-order*** system to a lower-order system.
- Extend our framework to deal with learners with ***more capabilities*** than the teacher

THANK YOU!

UVA ENGINEERING

LINK LAB

Shijie Gao: sjgao@virginia.edu

https://www.bezzorobotics.com

DARPA