Adaptive Distribution of a Swarm of Heterogeneous Robots

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Workshop on On-line decision-making in multi-robot coordination
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Penn Engineering | GRASP Laboratory
General Robotics, Automation, Sensing & Perception Lab

Introduction

How do we design *heterogeneous* multi-robot systems to maximize performance?

Diversity Metric

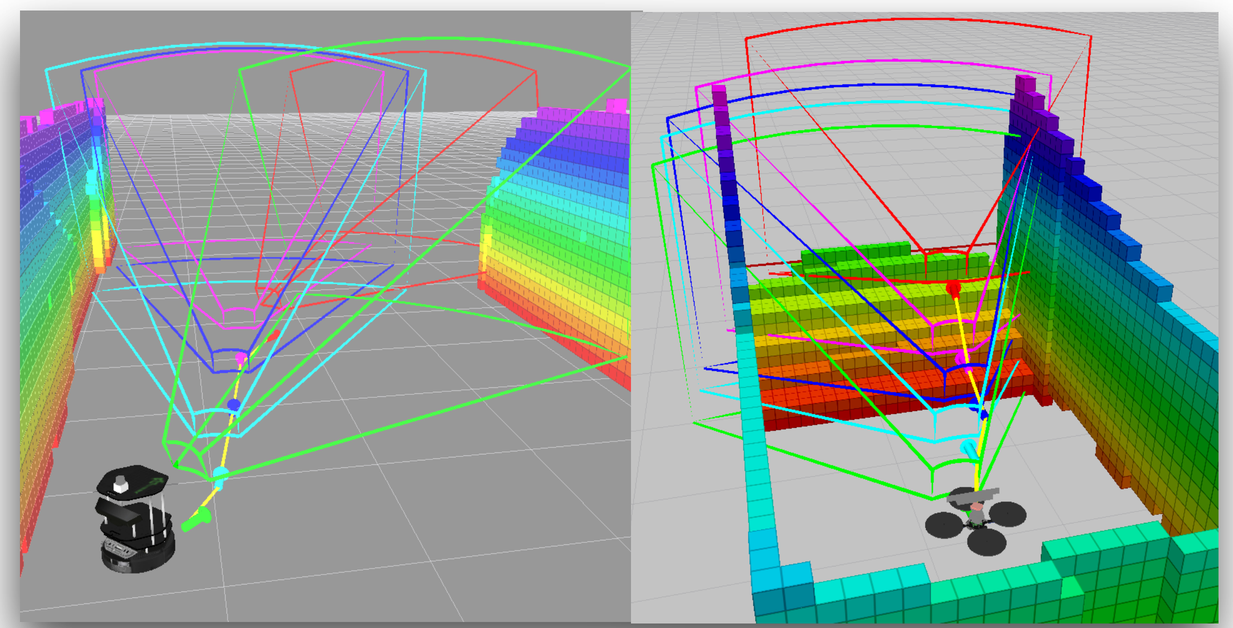
Design Paradigm

* Image credits: M. Egerstedt, Georgia Tech

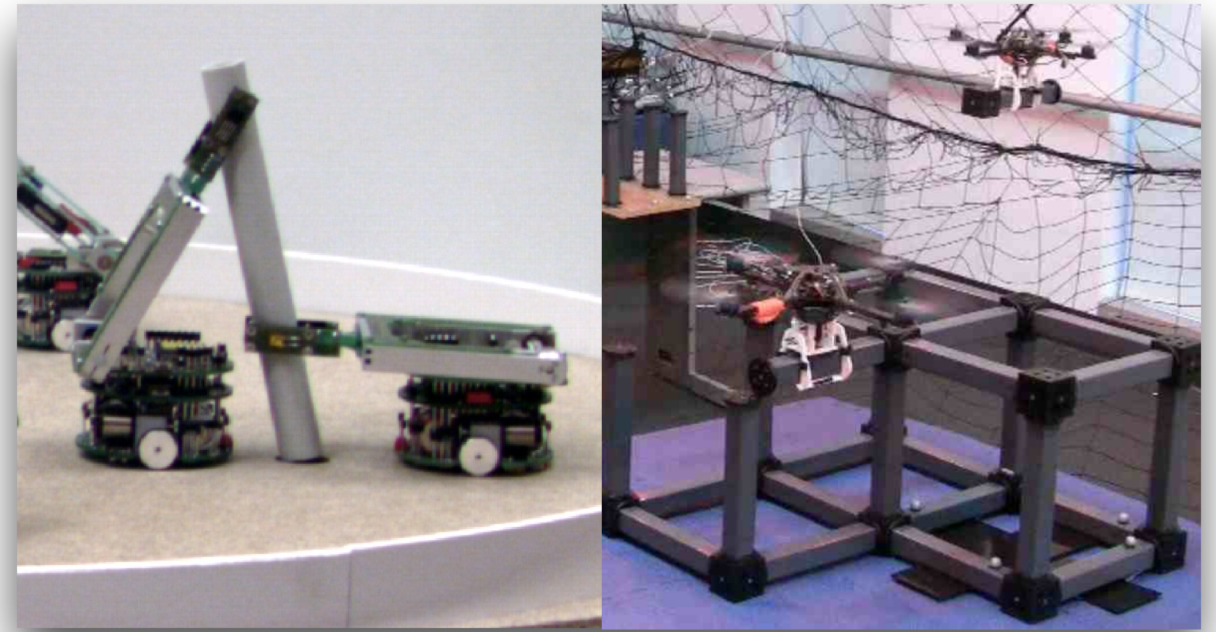
Examples

One robot type cannot cater to all aspects of a task

Collaborative Perception



Collaborative Manipulation

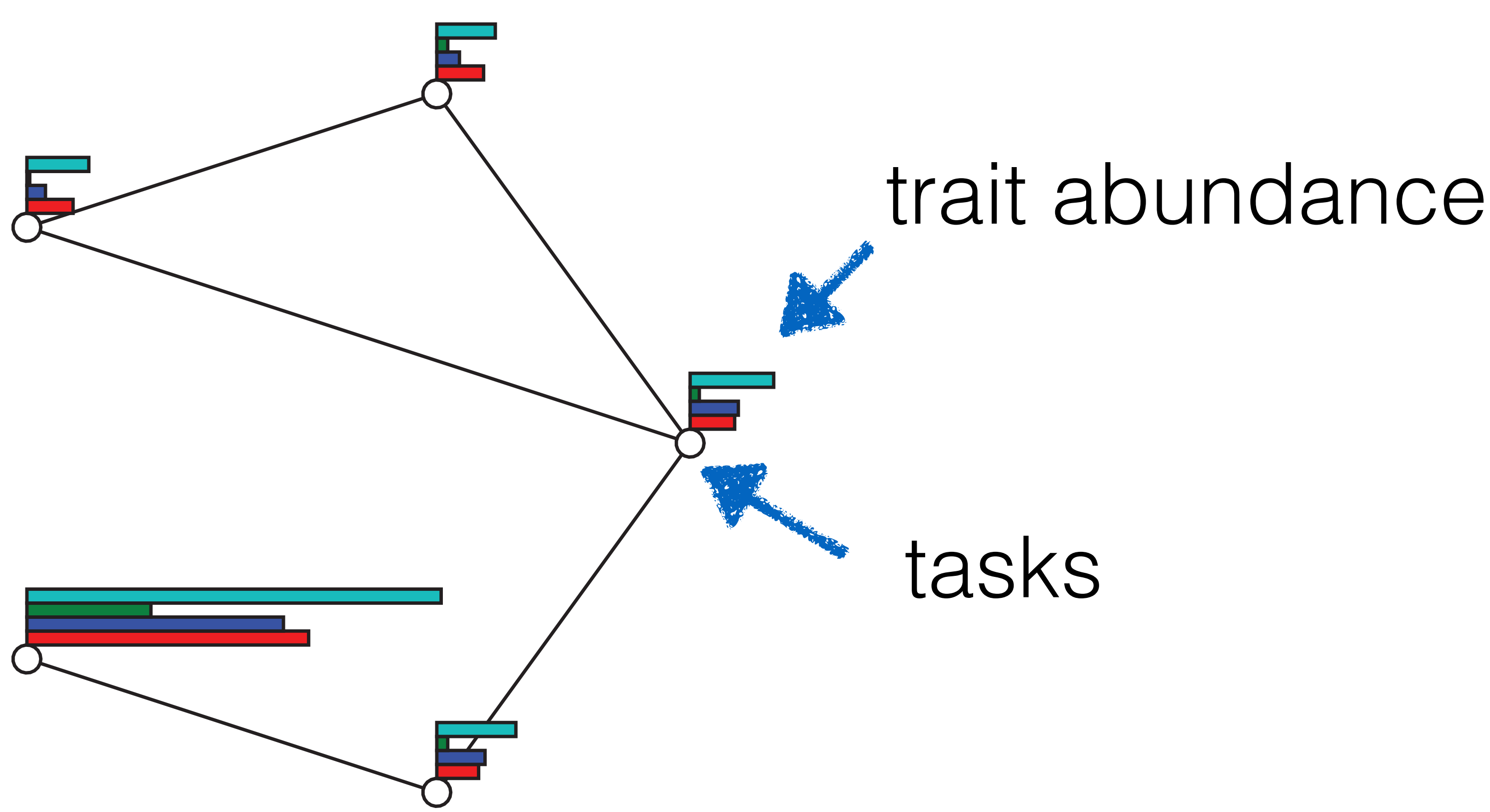


Idea: A task needs certain capabilities

Approach

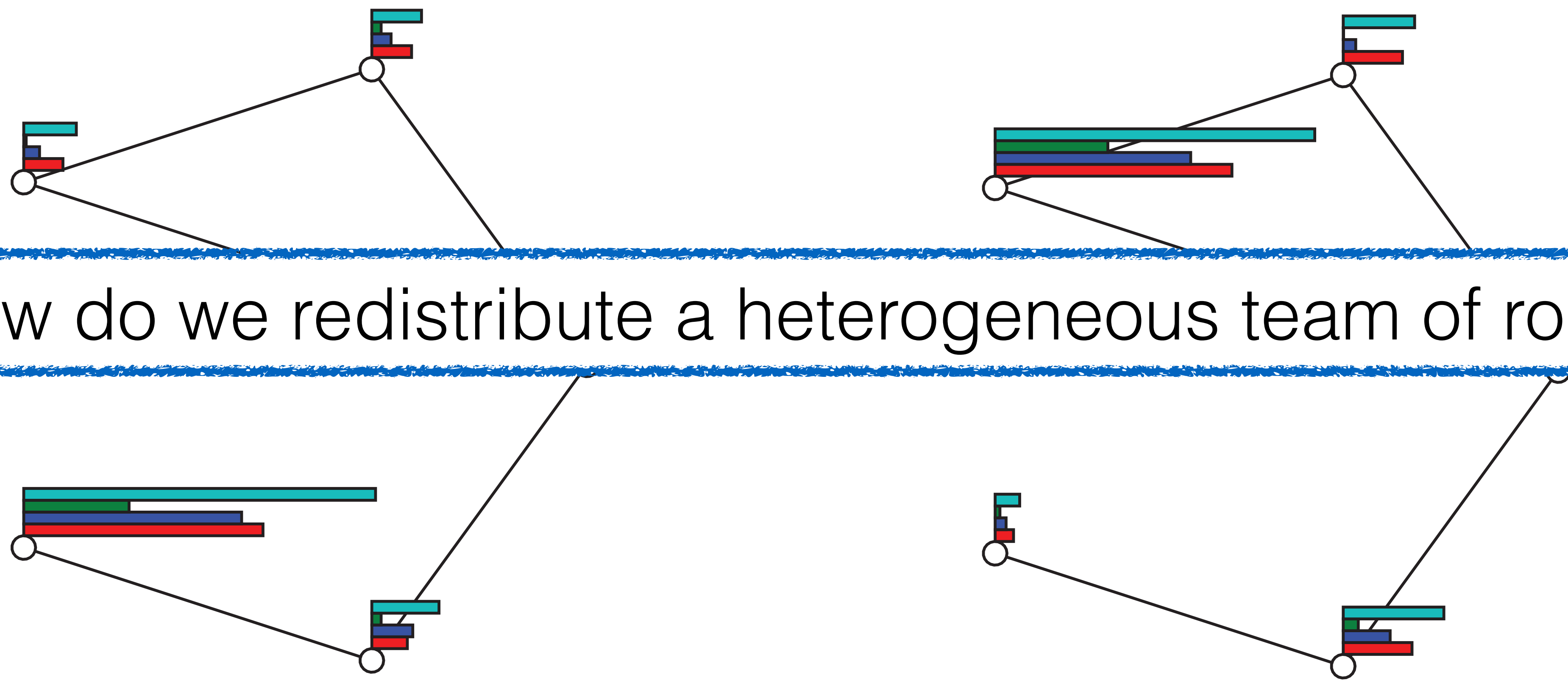
Robot community
- Species
- Binary traits

Tasks
- Need traits
- Switching



trait distribution

Problem Formulation



How do we redistribute a heterogeneous team of robots?

initial → target

Redistribution of traits (capabilities) among tasks

System

$$\mathbf{Y}(t) = \mathbf{X}(t) \cdot \mathbf{Q}$$

trait distribution

robot distribution

species-traits matrix

$$\mathbf{Q} = \begin{array}{cc} \text{traits} & \\ \begin{pmatrix} 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} & \text{species} \end{array}$$

Method

$$\frac{\mathrm{d}\mathbf{x}^{(s)}}{\mathrm{d}t} = \mathbf{K}^{(s)}\mathbf{x}^{(s)}$$

— for a large number of robots, model system as ODE

$$\mathbf{K}^{(s)}$$

— transition rates for each species

$$\mathbf{Y}(t) = \mathbf{X}(t) \cdot \mathbf{Q}$$

— system

$$\mathbf{Y}(t) = \sum_{s=1}^{S} e^{\mathbf{K}^{(s)\star} t} \mathbf{x}_0^{(s)} \cdot \mathbf{q}^{(s)}$$

— solution to the ODE

Method

$$\mathbf{E} = \mathbf{Y}^{\star} - \sum_{s=1}^{S} e^{\mathbf{K}^{(s)\star}\tau}\mathbf{x}_0^{(s)} \cdot \mathbf{q}^{(s)}$$

— error in trait distribution

1. minimize $\mathcal{J}^{(1)} = \| \mathbf{E} \|_F^2$

— basic optimization problem

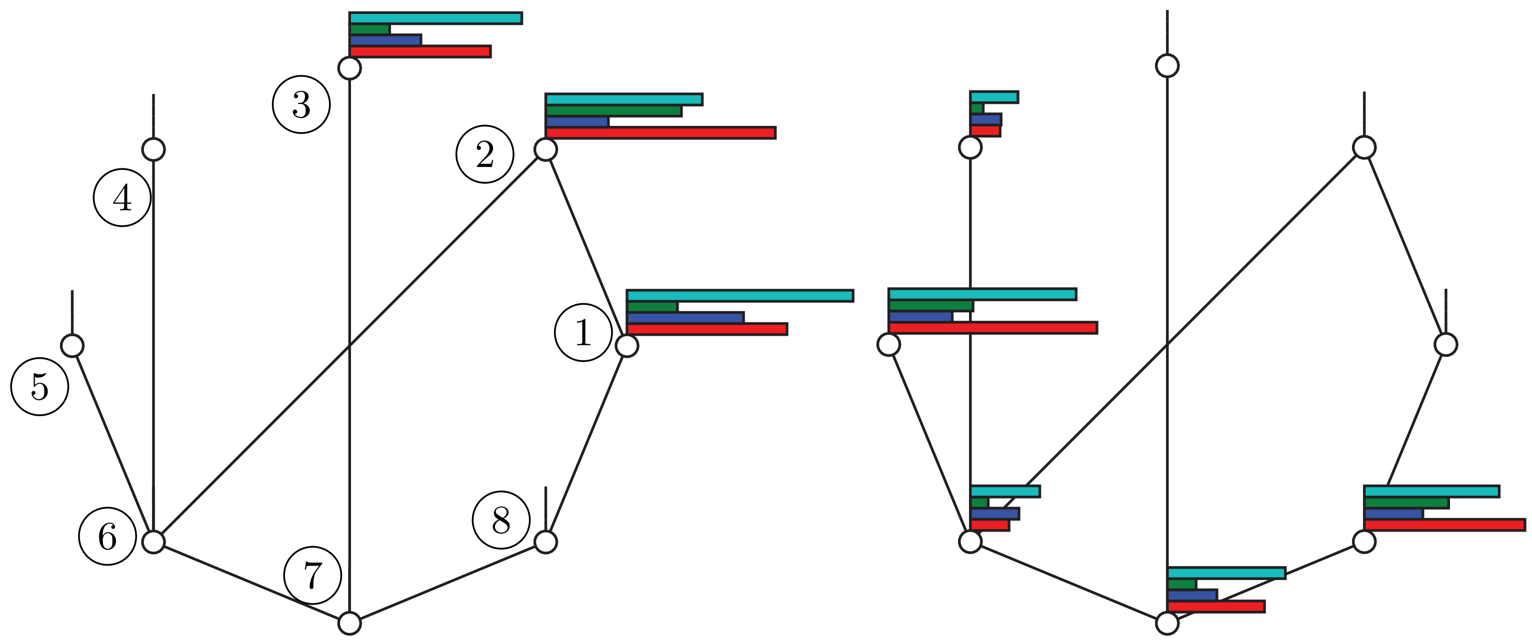
2. minimize $\mathcal{J}^{(2)} = \mathcal{J}^{(1)} + \alpha\tau^2$

— explicit opt. of convergence time

3. minimize $\mathcal{J}^{(3)} = \mathcal{J}^{(2)} + \beta \sum_{s=1}^{S} \left\| e^{\mathbf{K}^{(\mathbf{s})}\tau}\mathbf{x}_0^{(s)} - e^{\mathbf{K}^{(\mathbf{s})}(\tau+\nu)}\mathbf{x}_0^{(s)} \right\|_2^2$

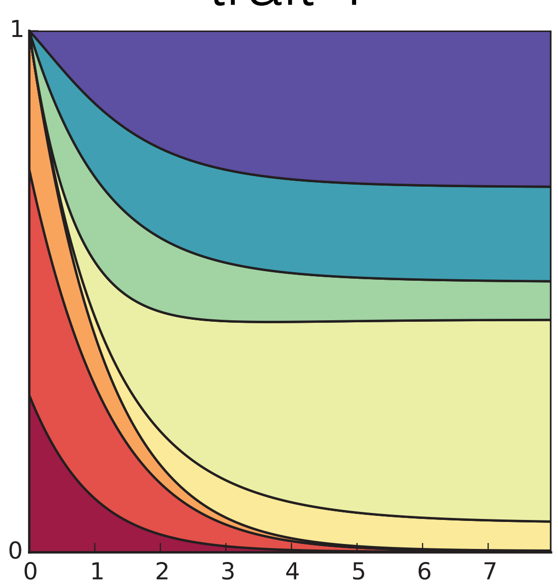
— reinforcing steady-state

Example

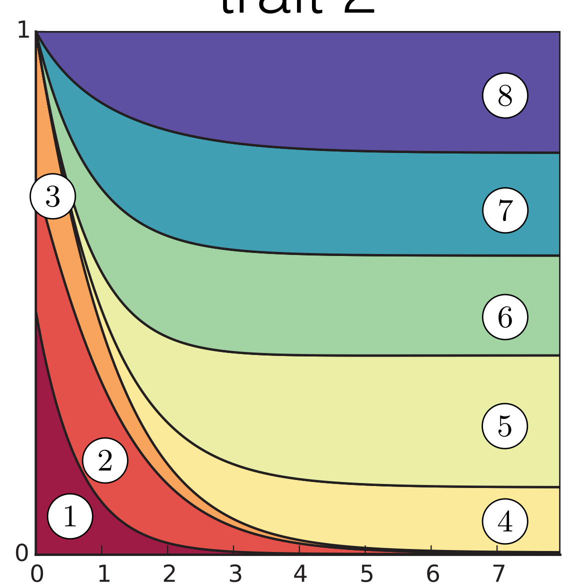


initial → target

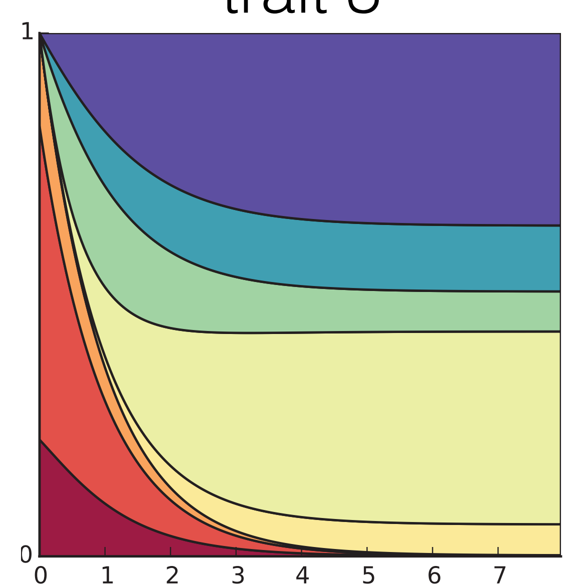
trait 1



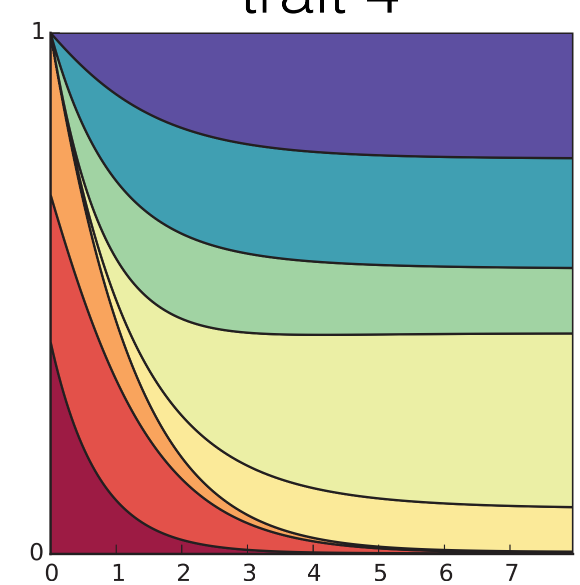
trait 2



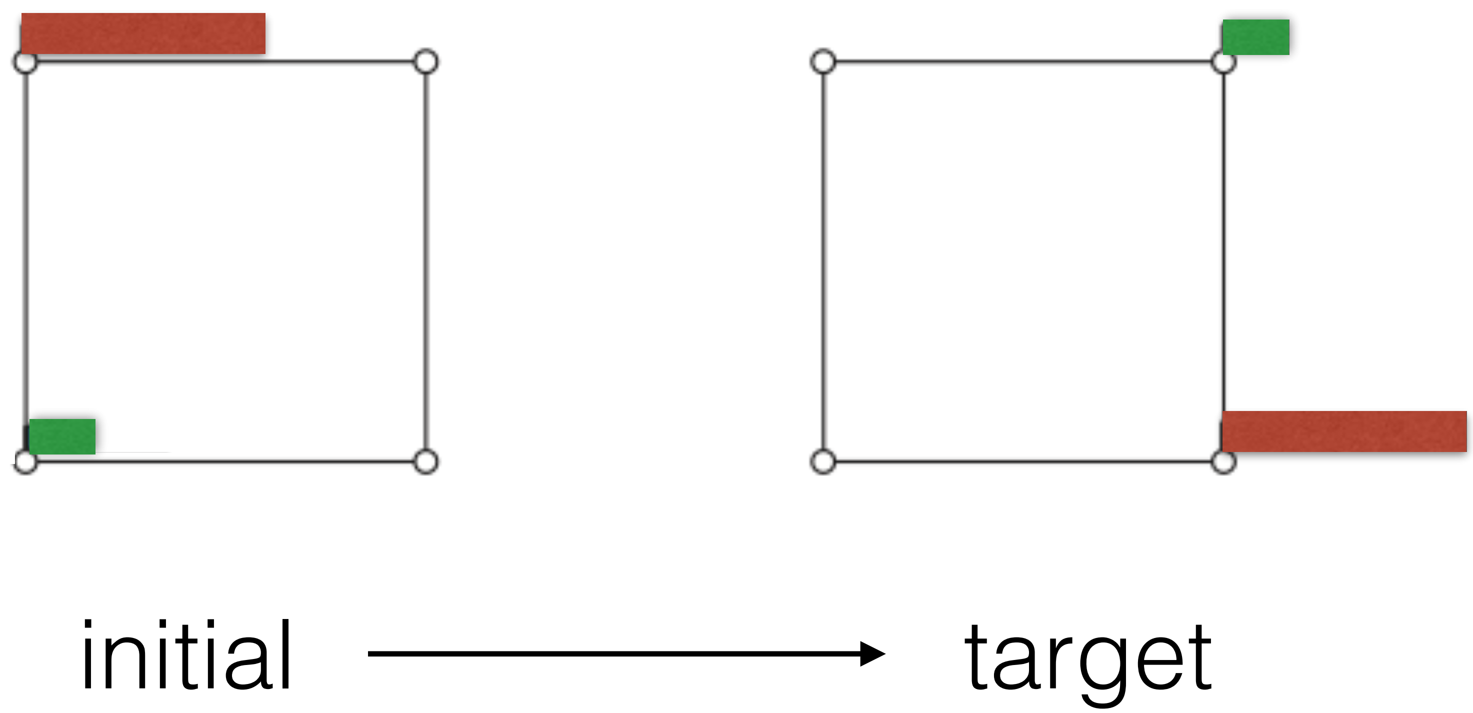
trait 3

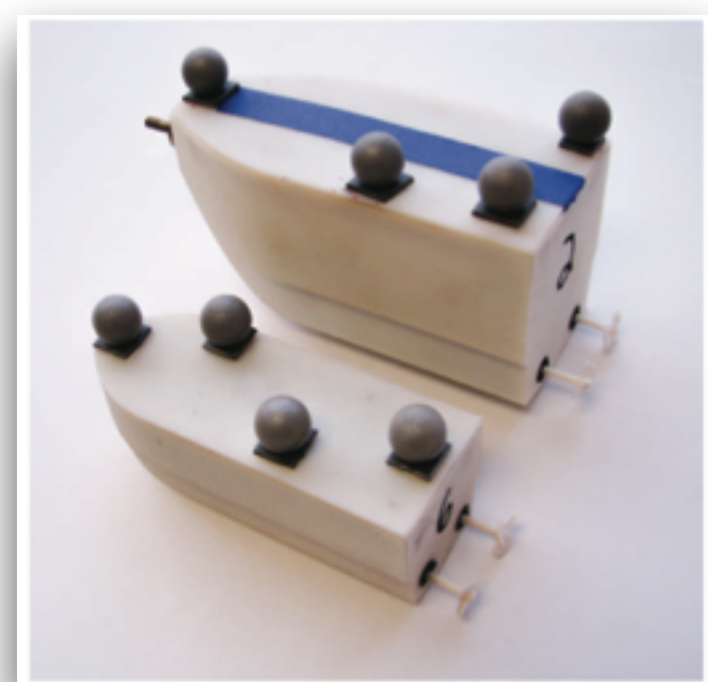


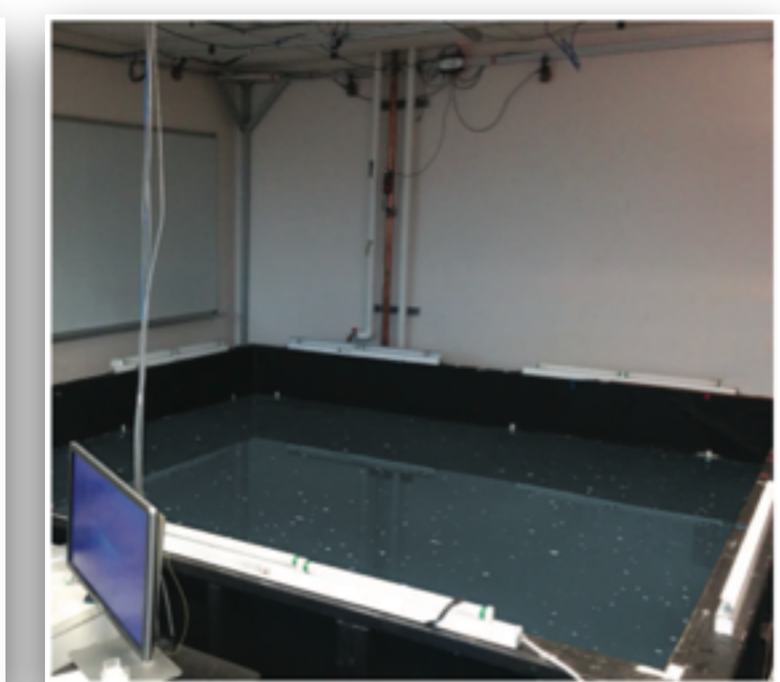
trait 4



Experiment







* Work submitted to ICRA 2016

Movie

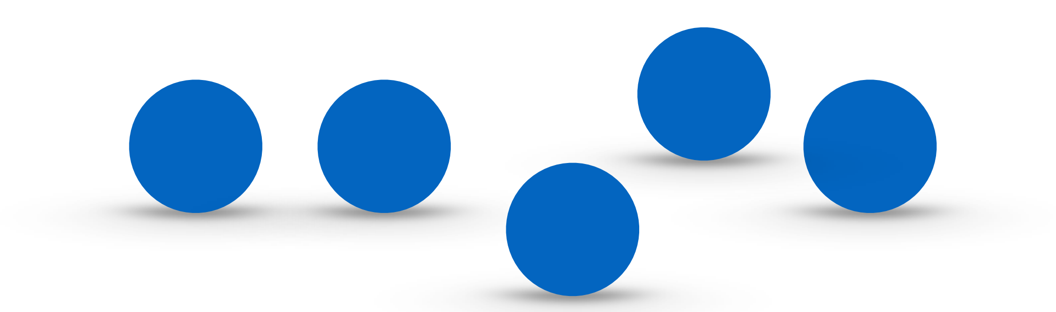
submitted to ICRA 2016

Continuous Optimization

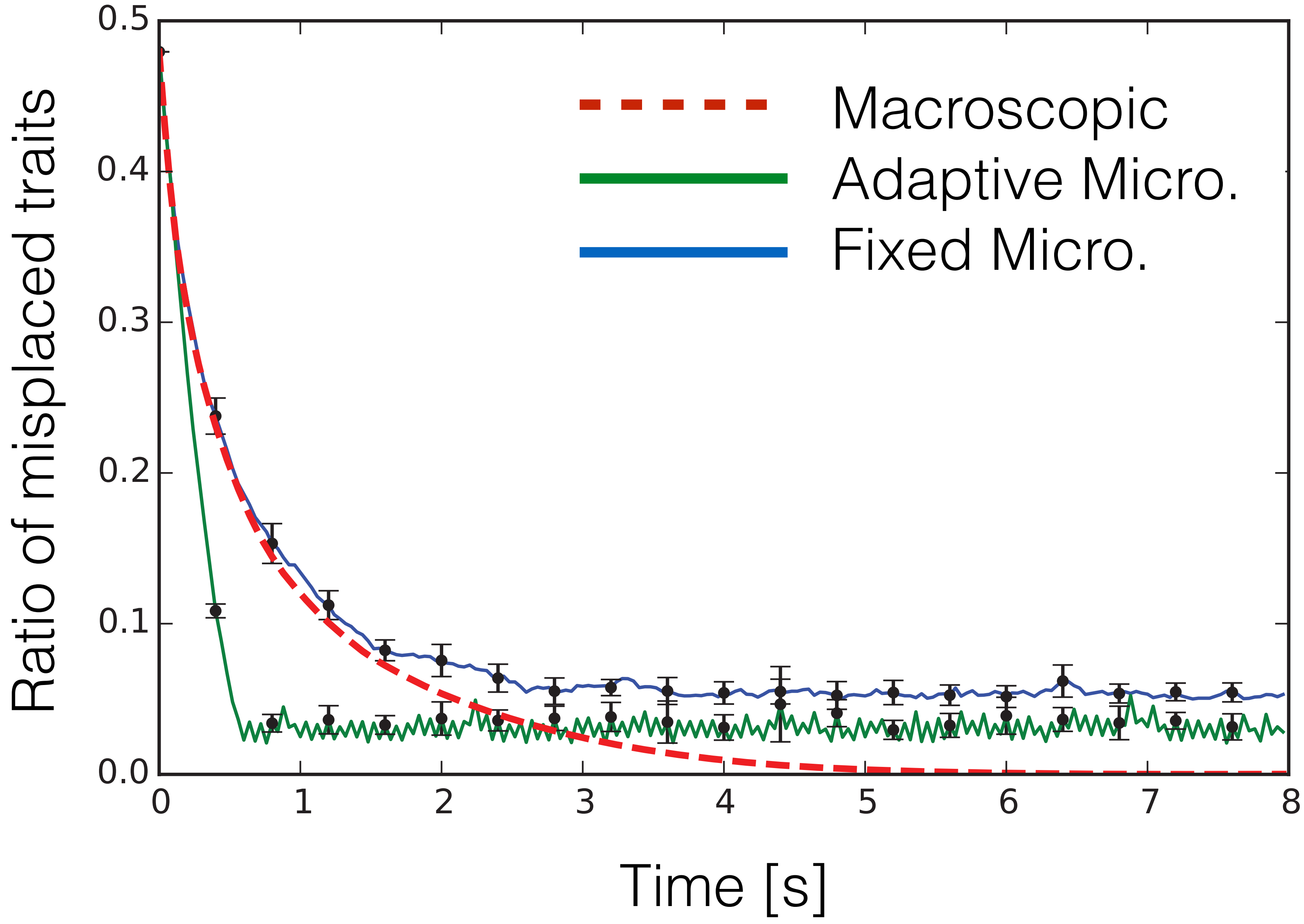
Fixed K: $$\mathbf{K}^{(s)\star}, \tau^\star = \underset{\mathbf{K}^{(s)}, \tau}{\operatorname{argmin}} \mathcal{J}^{(3)}$$

Adaptive K: $$\mathbf{K}^{(s)\star}(t), \tau^\star(t) \quad = \quad \underset{\mathbf{K}^{(s)}, \tau}{\operatorname{argmin}} \tilde{\mathcal{J}}^{(3)}(\mathbf{X}(t_p))$$

$$\mathbf{X}(t_p)$$

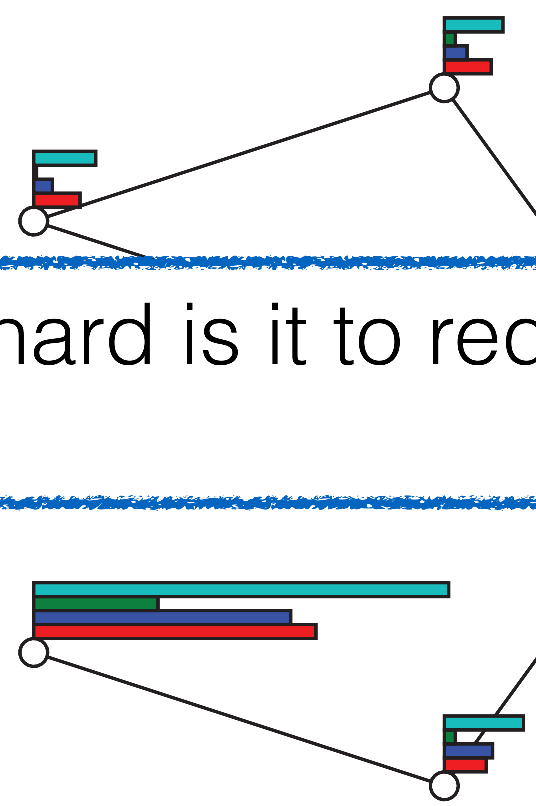


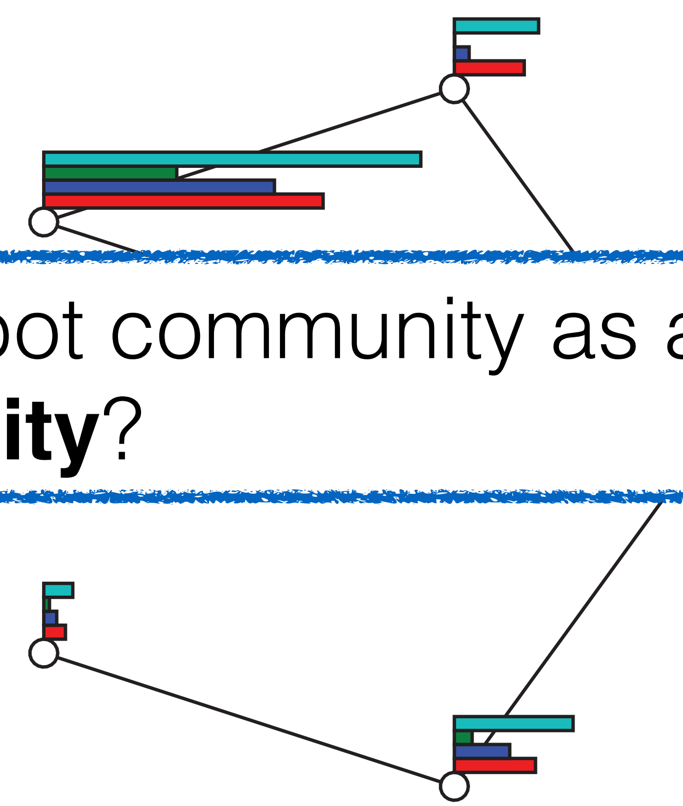
Results



Ratio of misplaced traits
0.5
0.4
0.3
0.2
0.1
0.0
0
1
2
3
4
5
6
7
8
Time [s]
Macroscopic
Adaptive Micro.
Fixed Micro.

Approach





How hard is it to redistribute the robot community as a function of its **diversity**?

initial → target

Effects of Diversity

$$\mathrm{rank}(\mathbf{Q}) = S$$

$$\mathbf{Q} = \begin{pmatrix} 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

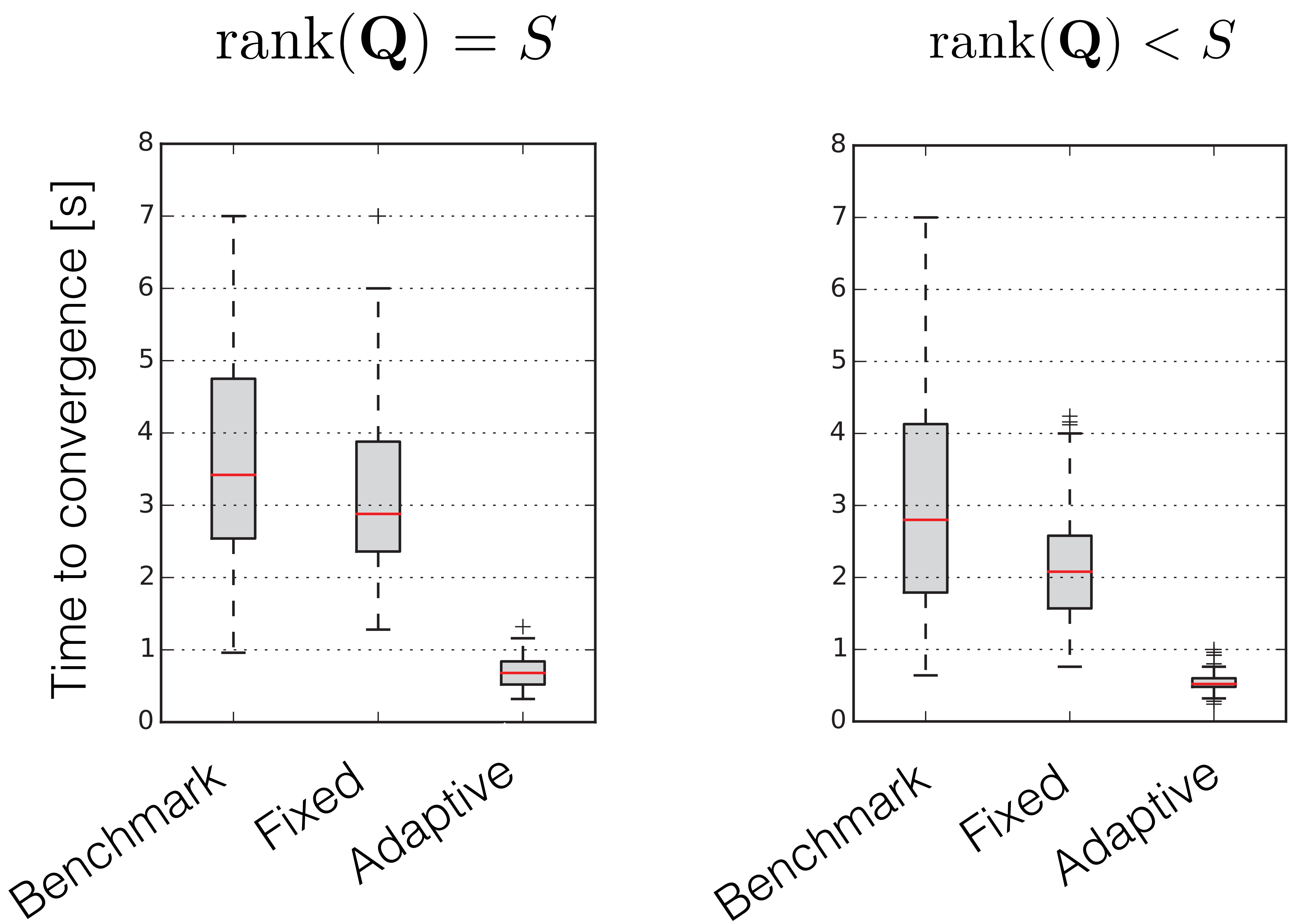
All species are independent

$$\mathrm{rank}(\mathbf{Q}) < S$$

$$\mathbf{Q} = \begin{pmatrix} 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix}$$

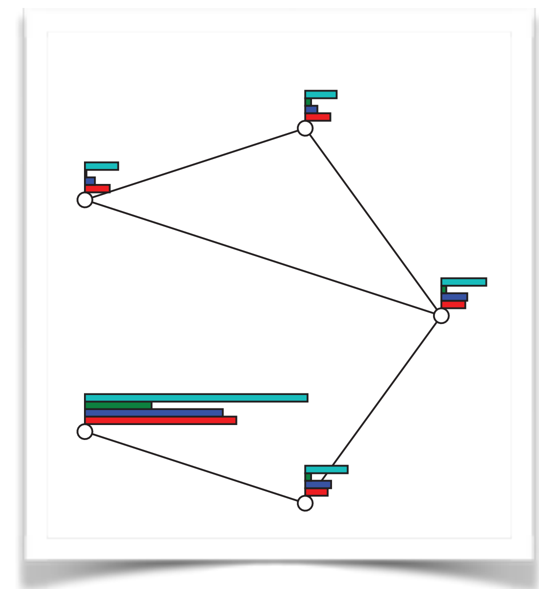
There are dependent species

Effects of Diversity



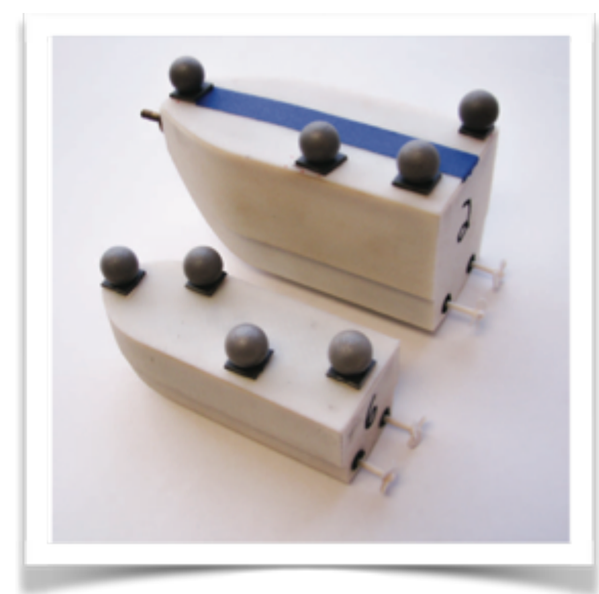
Conclusions

- Model for heterogeneous robot system
- Efficient optimization algorithm
- Formulation for adaptive control
- Real robot experiments
- Effects of diversity



Further work:

- Automatic generation of task requirements
- Continuous trait instantiations
- Foundations of diversity



Thank you for your attention.

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