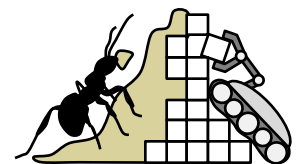


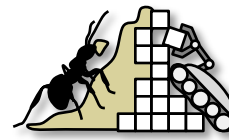
# Designing Robot Collectives

*by Kirstin Petersen  
July 2017*



Collective Embodied  
Intelligence Lab

# Motivation

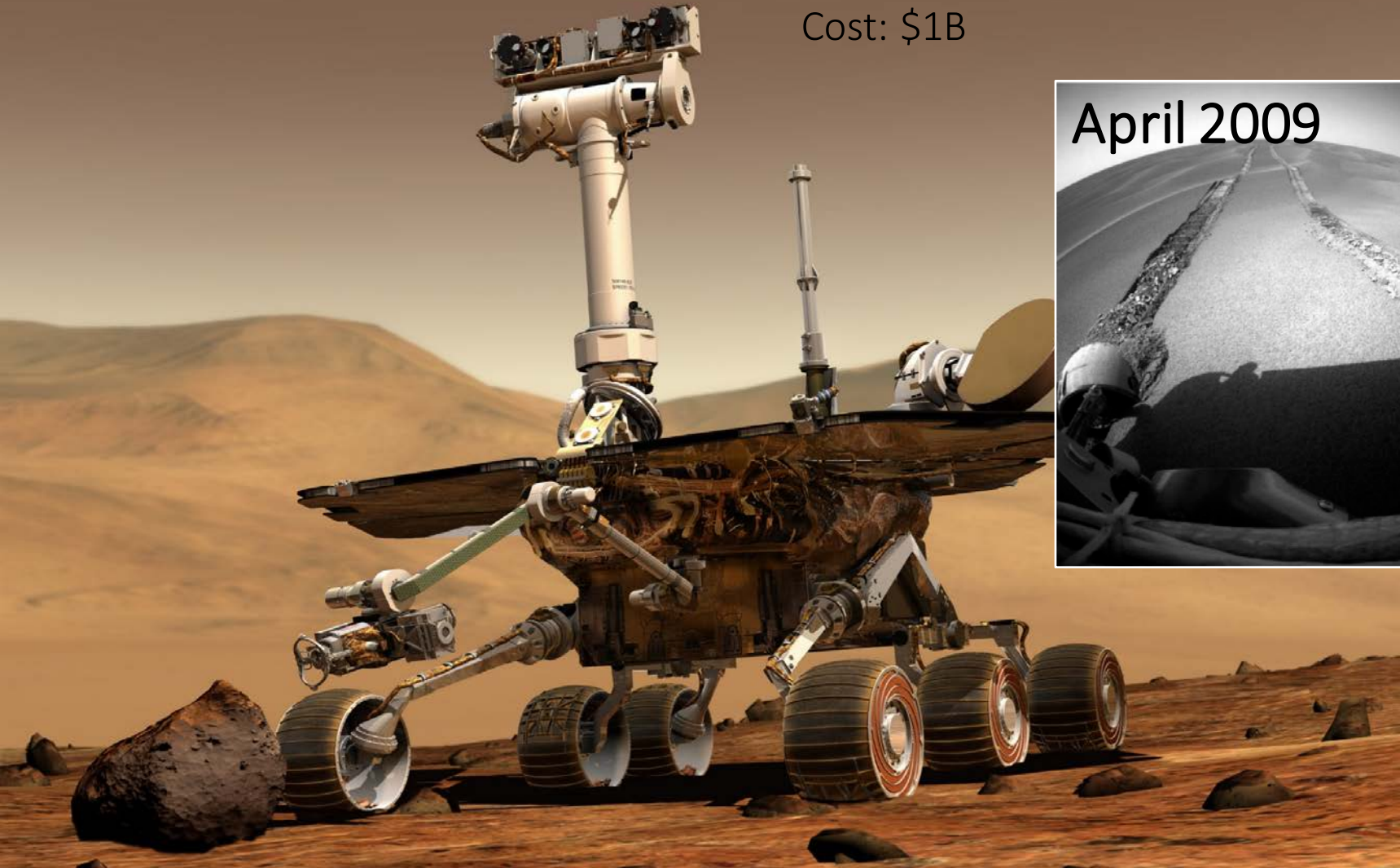


Collective Embodied  
Intelligence Lab

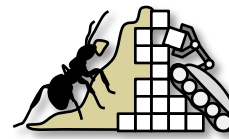


January 2004

Distance to Mars: 34-250M miles  
Travel time: 39-289 days  
Cost: \$1B



# Designing Robot Collectives



Collective Embodied  
Intelligence Lab



*Instead of sending one, we  
could send collectives!*

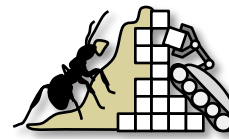
- Robustness
- Efficiency
- Capability



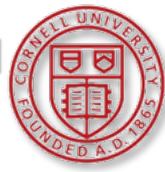


# Robot Collectives

## Success Stories!



Collective Embodied  
Intelligence Lab

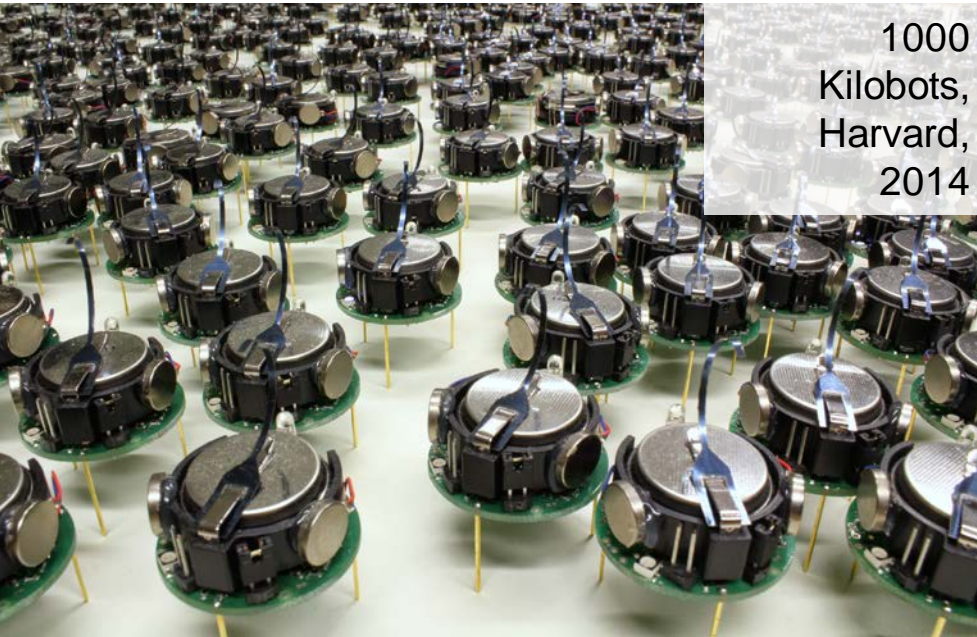


*Still challenging*

- ...to operate collectives
- ...to make capable, expendable robots
- ...to coordinate collectives



Amazon Robotics,  
automated warehouses

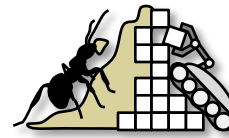


1000  
Kilobots,  
Harvard,  
2014



103 drones in flight  
Dr. Timothy Chung, DARPA

# Designing Robot Collectives



Collective Embodied  
Intelligence Lab



## *Control*

(Remote Controlled)

Autonomy/  
Taskability

(Exact number)

Scalable

**HOLLISTIC DESIGN  
APPROACH**

Error Tolerance

## *Hardware*

(Stationary)

**SOFTWARE  
HARDWARE  
ENVIRONMENT**

Capability

**RELIABILITY  
ERROR TOLERANCE**

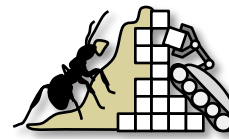
Cost

Maintenance

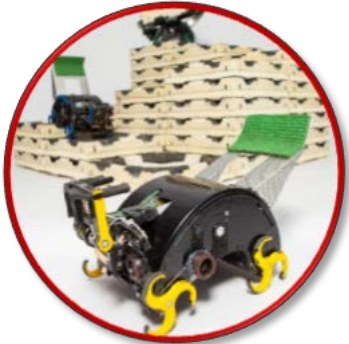
**COLLECTIVES  
IN NATURE**



# Designing Robot Collectives



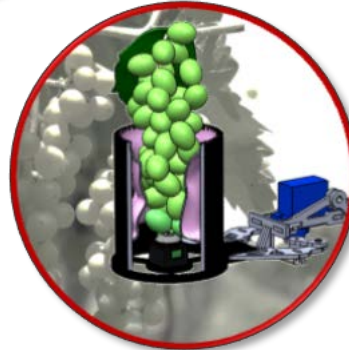
Collective Embodied  
Intelligence Lab



Swarm  
Support  
Systems



Coordination  
in Nature



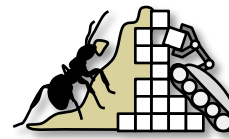
Natural  
Mechanisms

Soft  
Robots

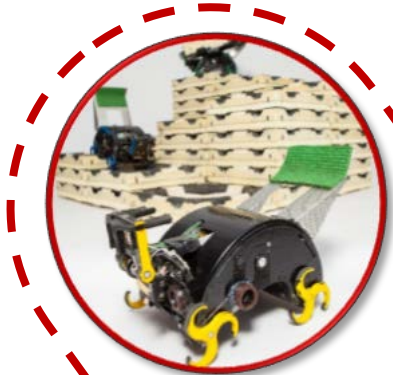


Collective  
Construction

# Designing Robot Collectives



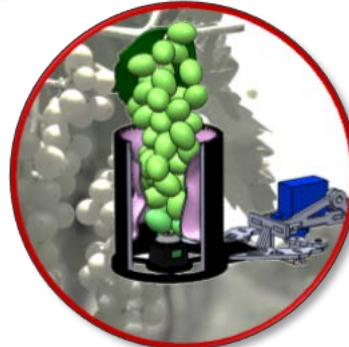
Collective Embodied  
Intelligence Lab



Swarm  
Support  
Systems



Coordination  
in Nature

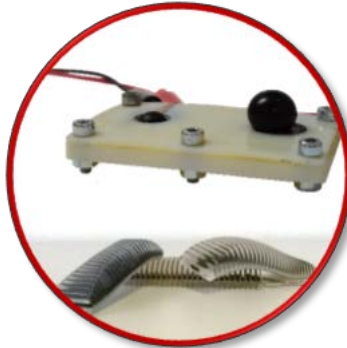


Natural  
Mechanisms

Soft  
Robots



Collective  
Construction



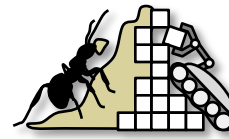






# Macrotermes Studies

...with Dr. Paul Bardunias, Dr. Justin Werfel, Prof. Radhika Nagpal, Prof. Nils Napp, Prof. Scott Turner



Collective Embodied  
Intelligence Lab

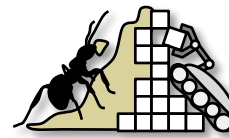


- Decentralized
- Parallelism
- Simple agents
- Simple environment
- Error tolerant
- Guaranteed high-level outcome



# Termite-Inspired Collective Construction

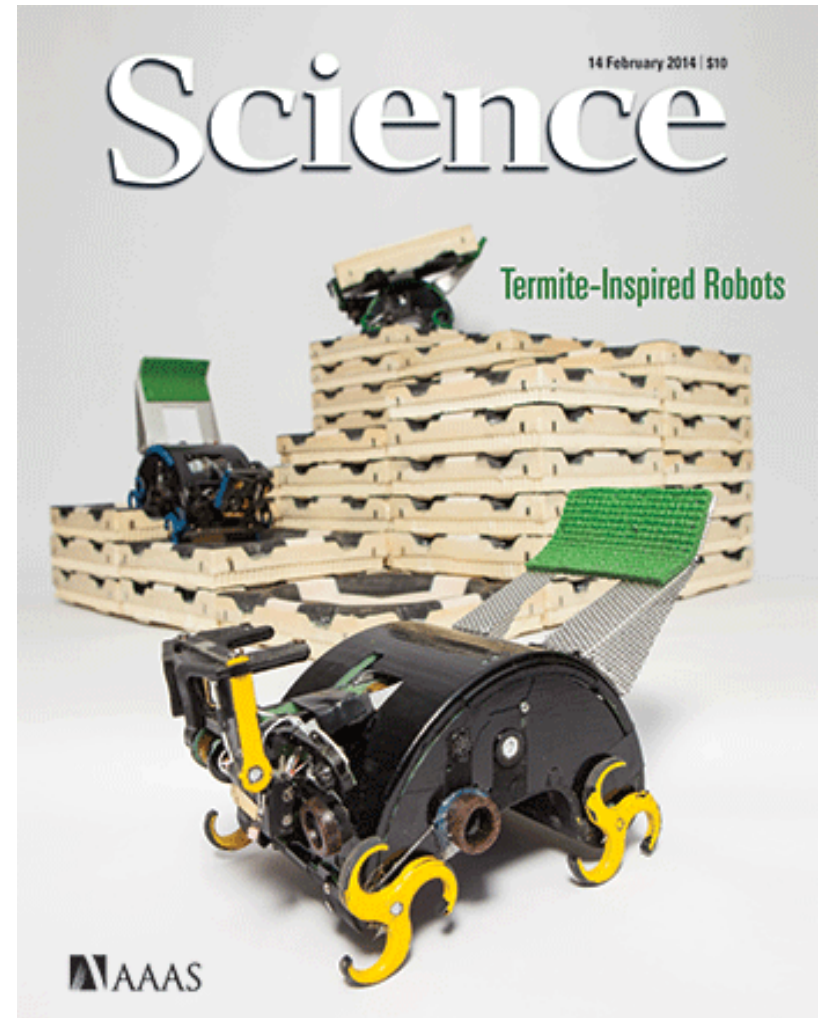
...with Dr. Justin Werfel and Prof. Radhika Nagpal, Harvard



Collective Embodied  
Intelligence Lab



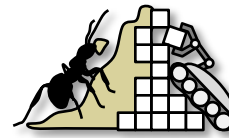
- Decentralized
- Parallelism
- Simple agents
- Simple environment
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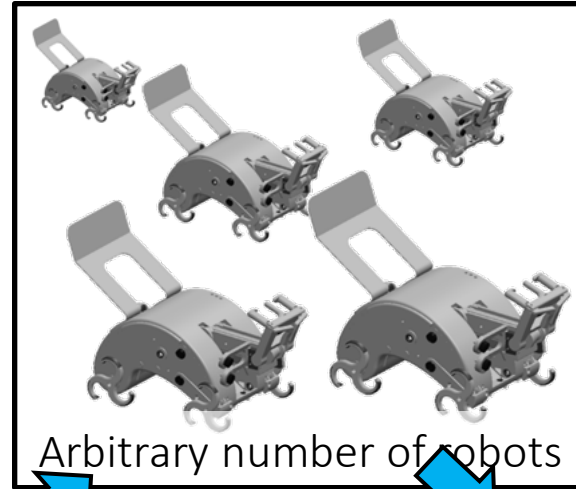
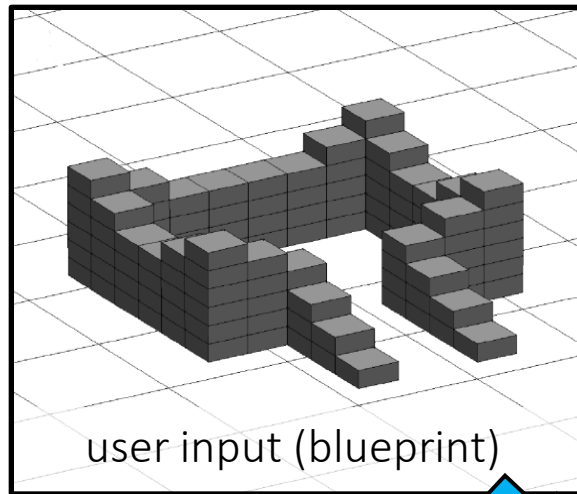


# TERMES Algorithms

...with Dr. Justin Werfel and Prof. Radhika Nagpal, Harvard



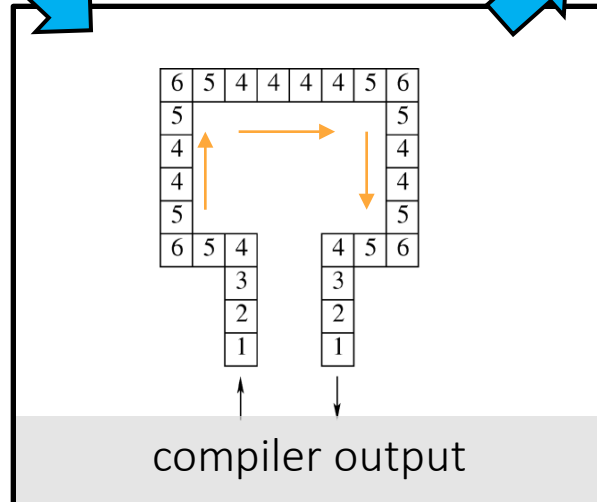
Collective Embodied  
Intelligence Lab



+internal rule set

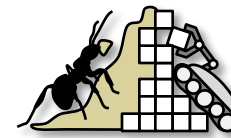
- No gaps
- No cliffs

Off-line  
compiler step  
generates  
traffic patterns



# TERMES Implementation

...with Dr. Justin Werfel and Prof. Radhika Nagpal, Harvard



Collective Embodied  
Intelligence Lab



Locomotion



Navigation



Manipulation



Co-Design & Error Tolerance



Coordination



Control



Fabrication

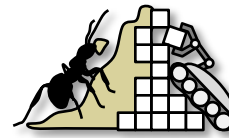


Petersen, Kirstin, Radhika Nagpal, and Justin Werfel. "Termes: An autonomous robotic system for three-dimensional collective construction." *Proc. Robotics: Science & Systems VII* (2011).

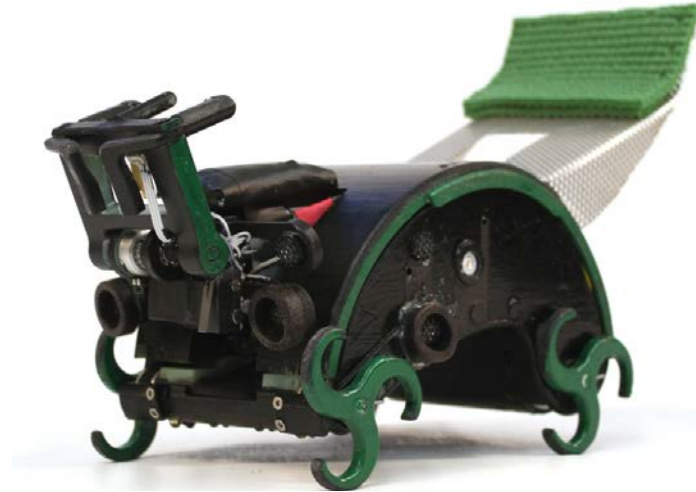
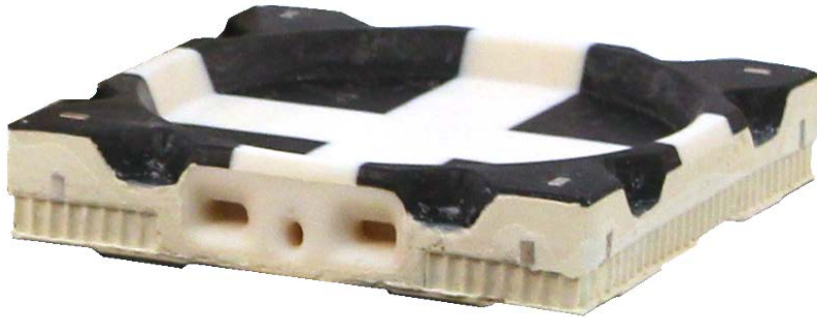


# TERMES Locomotion

...with Dr. Justin Werfel and Prof. Radhika Nagpal, Harvard

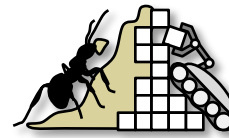


Collective Embodied  
Intelligence Lab

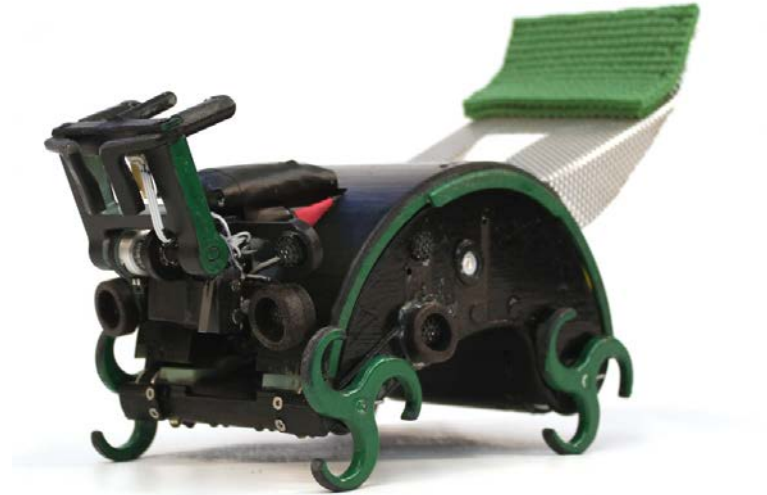
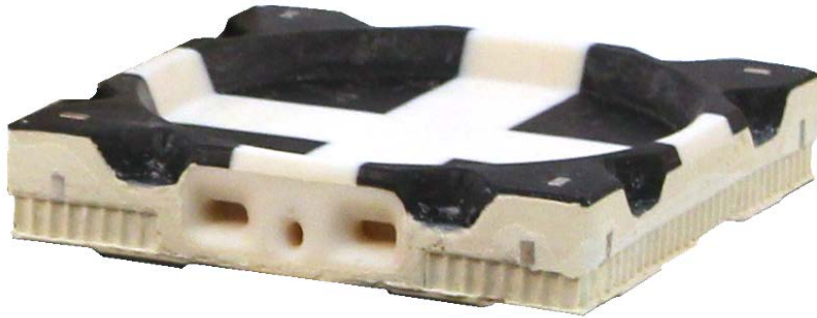


# TERMES Navigation

...with Dr. Justin Werfel and Prof. Radhika Nagpal, Harvard



Collective Embodied  
Intelligence Lab

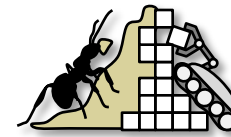


- 3 actuators
- Infrared (pattern recognition)
- Accelerometer (climbing)
- Tactile sensing (brick manipulation)
- Ultrasound (wall following/avoidance)
- Control by simple FSM



# TERMES Summary

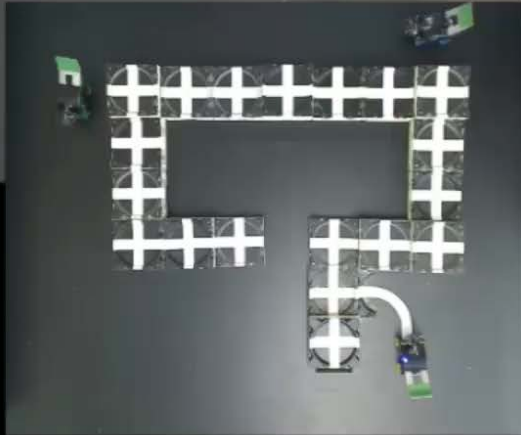
...with Dr. Justin Werfel and Prof. Radhika Nagpal, Harvard



Collective Embodied  
Intelligence Lab



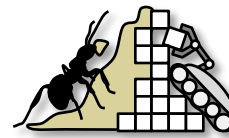
Minimalist solution through *embodied intelligence* and *error tolerant* control



Werfel, J, K Petersen, & R Nagpal. 2014. Designing collective behavior in a termite-inspired robot construction team. *Science* 343(6172):754-758 (2014).

x50

# Designing Robot Collectives

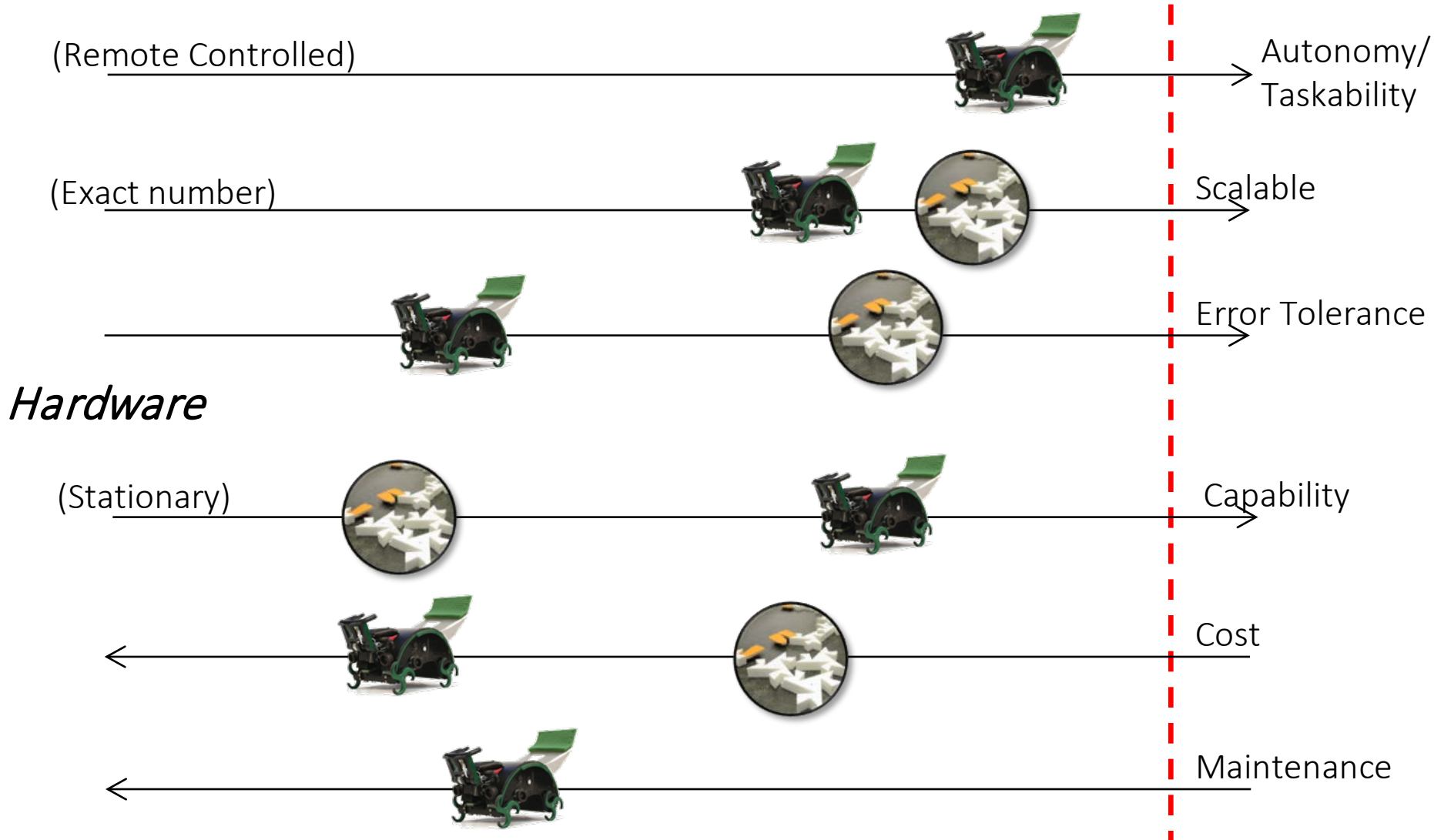


Collective Embodied  
Intelligence Lab



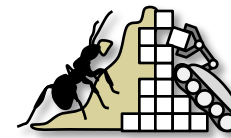
## *Control*

Andreen, D, P. Jennings, N. Napp, and K. Petersen. 2016. Emergent Structures Assembled by Large Swarms of Simple Robots. ACADIA // 2016, pp. 54-61.





# Designing Robot Collectives



Collective Embodied  
Intelligence Lab



## *Control*

Spröwitz, A., Göttler, C., Sinha, A., Caer, C., Oztekin, M. U., Petersen, K., & Sitti, M. Scalable Pneumatic and Tendon Driven Robotic Joint Inspired by Jumping Spiders. ICRA 2017.

(Remote Controlled)

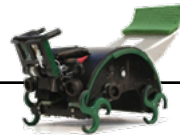


Autonomy/  
Taskability

(Exact number)



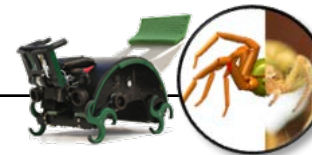
Scalable



Error Tolerance

## *Hardware*

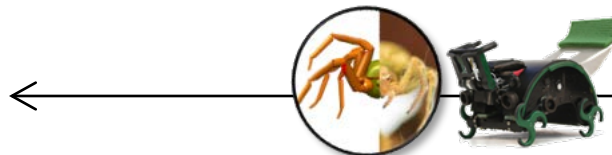
(Stationary)



Capability

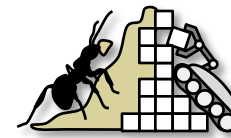


Cost

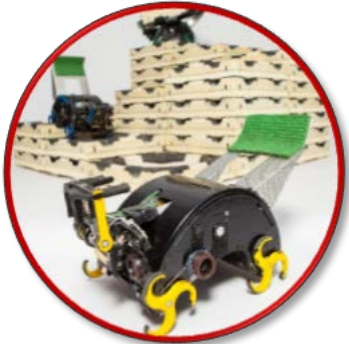


Maintenance

# Designing Robot Collectives



Collective Embodied  
Intelligence Lab

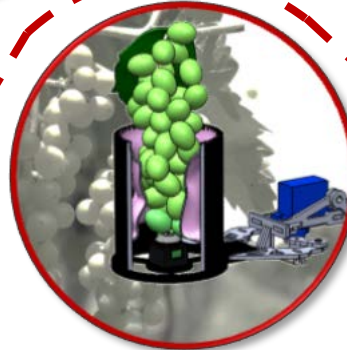


Swarm  
Support  
Systems



Collective  
Construction

Coordination  
in Nature

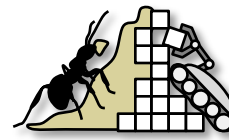


Natural  
Mechanisms

Soft  
Robots



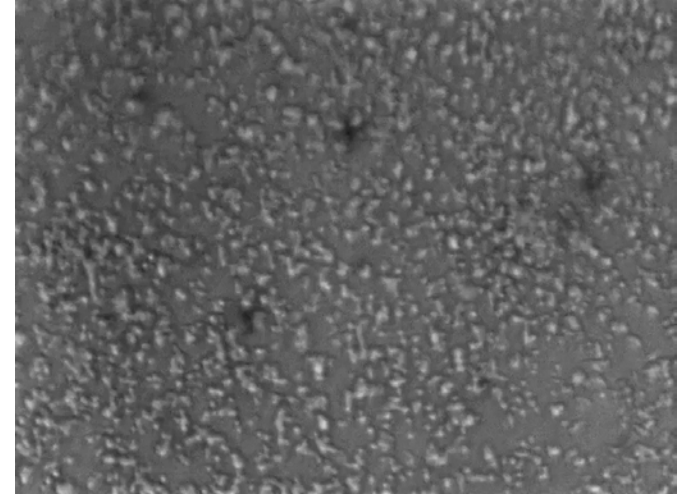
# Soft Robot Collectives



Collective Embodied  
Intelligence Lab



- Operation in unstructured terrain
- Resilient
- Inexpensive
- Compliant and safe

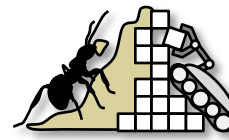


*D. discoideum* (slime mold)  
Bonner, Princeton, 1984





# Soft Robot Collectives



Collective Embodied  
Intelligence Lab

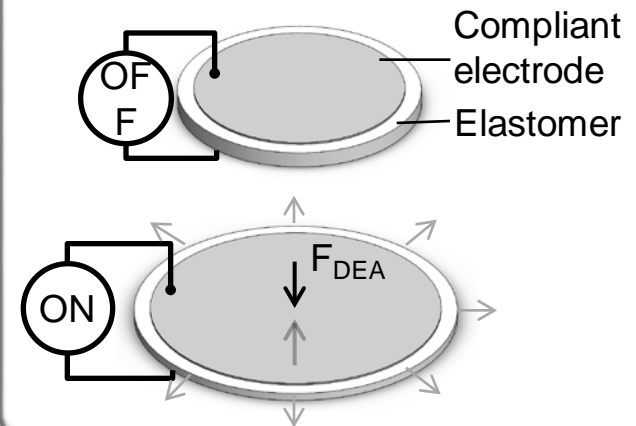


*Compact, simple, soft actuator with large, stable, and repeatable shape changes.*

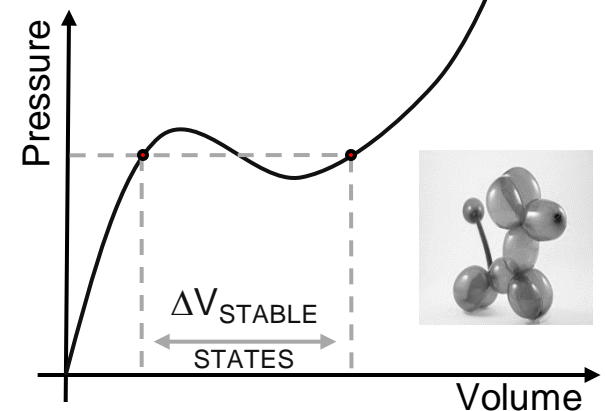
Hines\*, L, Petersen\*, K. and Sitti, M. (2016) Inflated Soft Actuators with Reversible Stable Deformations. *Advanced Materials*, 28(19), 3690-3696.

- "Asymmetric Stable Deformations in Inflated Dielectric Elastomer Actuators." Intl. Conf. of Robotics and Automation, 2017.

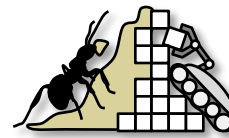
## Dielectric Elastomer Actuators



## Hyperelastic Materials



# Designing Robot Collectives

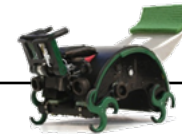


Collective Embodied  
Intelligence Lab



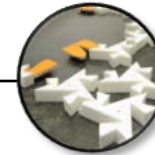
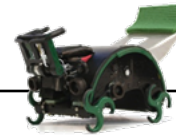
## *Control*

(Remote Controlled)



Autonomy/  
Taskability

(Exact number)



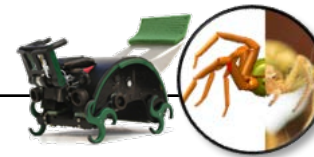
Scalable



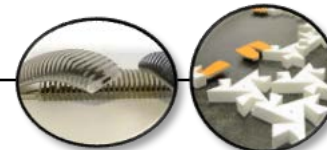
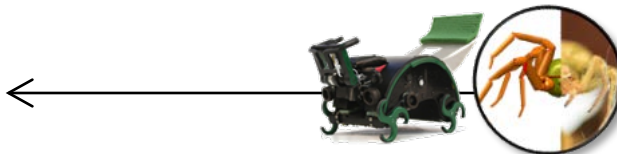
Error Tolerance

## *Hardware*

(Stationary)



Capability



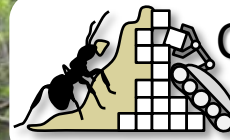
Cost



Maintenance

*\*Guestimates!*





Collective Embodied  
Intelligence Lab



Daniel Kim, Ryan O'Hern, Claire Chen, Kirstin Petersen, Vaidehi Patel, Yanir Nulman, Aasta Gandhi, Asena Ulug, Yejing Wang, Tim Duggan, Owen Hua, Yawen Deng, Mateo Espinoza, and Lawrence Chen