Constraint-Based Control Design for Assured and Long-Duration Autonomy

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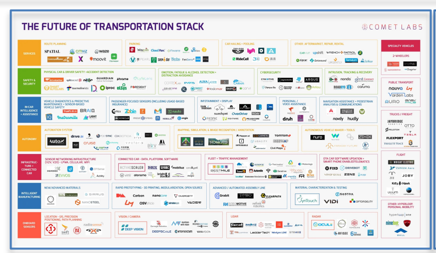
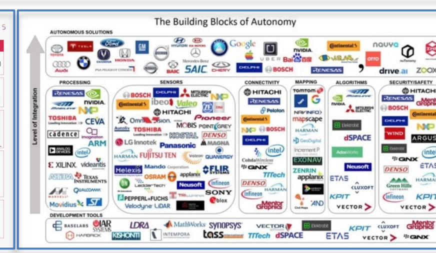
Long-Duration Autonomy?

A Canonical Autonomy Problem

<u>Don't hit stuff!</u>

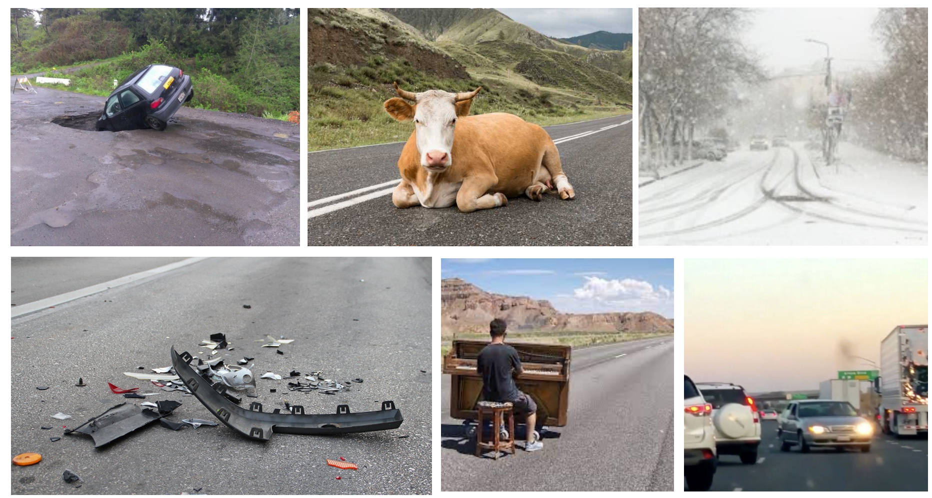
2007 DARPA Urban Challenge





The Hundred-Million-Mile Problem

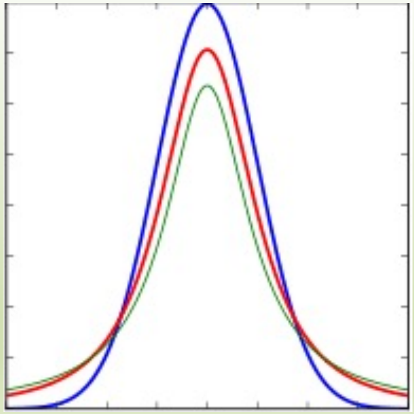
- A fatal accident happens in the US roughly every 100,000,000 miles when cars are piloted by human drivers
- Autonomous vehicles must exceed that number (by far)
- Lots of weird stuff on the road



K. H. Janstrup, *Road Safety Annual Report,* 2017

Heavy-Tail Distributions

- Uncommon events are common
  - Models? (Beyond the standard work horses: linearity and Gaussians)
  - Cannot discard/discount outliers
  - Cannot train on full-coverage data (game engines and simulators)



Three Observations About Long Duration Autonomy

Steinberg, Stack, Paluszkiewicz. Long Duration Autonomy: Challenges and Opportunities. *Autonomous Robots*, 2016.

I. Any attempt at enumerating everything the system might experience will fail.

II. The only way to understand systems that can be deployed over long periods of time is to deploy systems over long periods of time.

III. People are not optimal with regards to anything. Rather, we are remarkably adaptive and resilient.

Elephants Don’t Play Chess

Elephants Don't Play Chess

Rodney A. Brooks
MIT Artificial Intelligence Laboratory, Cambridge, MA 02139, USA

Robotics and Autonomous Systems 6 (1990) 3-15

Keywords: Situated activity; Mobile robots; Planning; Subsumption architecture; Artificial Intelligence.

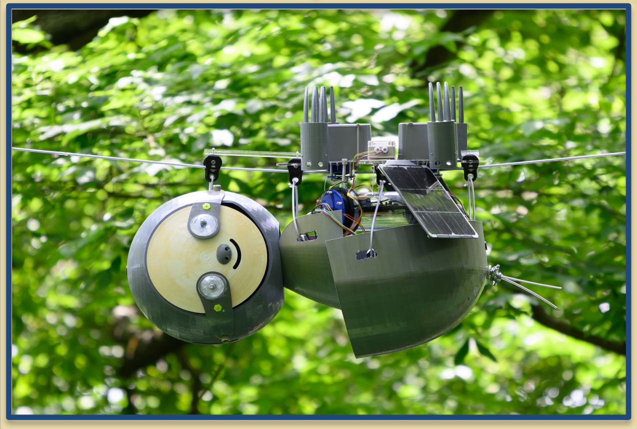
Rodney A. Brooks was born in Adelaide, Australia. He studied Mathematics at the Flinders University of South Australia and received a Ph.D. from Stanford in Computer Science in 1981. Since then he has held research associate positions at Carnegie Mellon University and the Massachusetts Institute of Technology and faculty positions at Stanford and M.I.T. He is currently an Associate Professor of Electrical Engineering and Computer Science at M.I.T. and a member of the Artificial Intelligence Laboratory where he leads the mobile robot group. He has authored two books, numerous scientific papers, and is the editor of the *International Journal of Computer Vision*.

The Route

I. Long Duration Autonomy

ROBOTARIUM

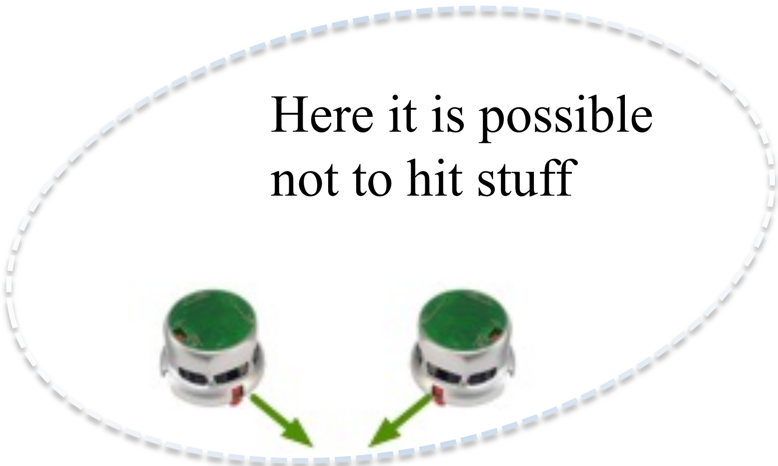
II. Swarm Robotics



III. Robot Ecology

A Possible Approach: Forward Invariance

Don't hit stuff!



Here it is ***not*** possible
not to hit stuff

Don't go unstable!

Don't run out of battery!

Don't get disconnected!

Don't get lost!

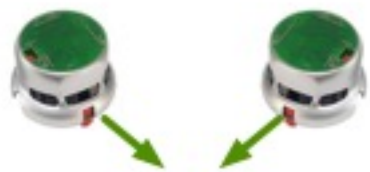
Don't lose coverage!

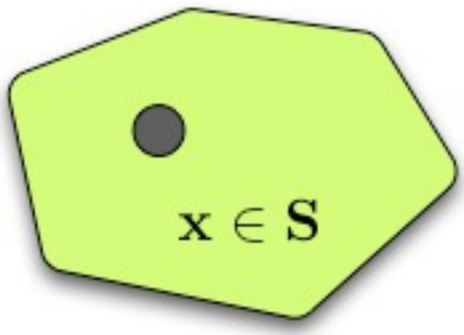
These examples all have the same structure: If the system starts in a certain "safe" set, it should remain in that safe set for all times = **FORWARD INVARIANCE!**

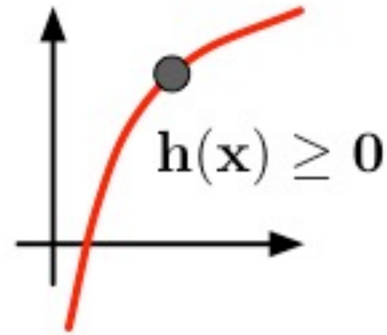
Example: Minimally Invasive Collision Avoidance

minimize: **"distance"** between actual input and nominal input
subject to: always stay **"safe"**

$$\dot{x}_i = f(x_i) + g(x_i)u_i$$







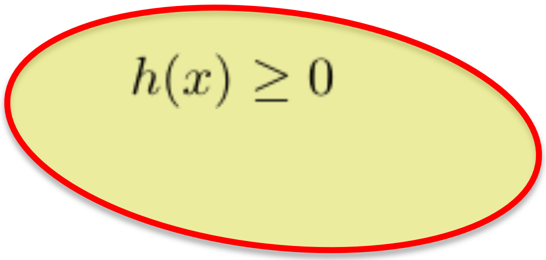
nominal controller/input

$$\min_{\mathbf{u}} \|\mathbf{u} - \mathbf{u}_n\|^2$$

$$\text{s.t. } \mathbf{h}(\mathbf{x}) \geq 0$$

Unfortunately, this is mathematical nonsense… Need a constraint involving ***u***!

A Key Result

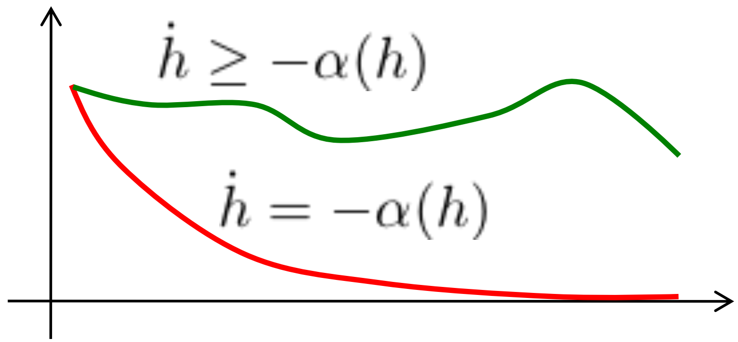


Theorem: The safe set is forward invariant if the control input satisfies

$$\dot{h}(x,u) \geq -\alpha(h(x))$$

for some extended class-K function

Ames, Xu, Grizzle, Tabuada, *TAC*'17; Ames, Coogan, Egerstedt, Notomista, Sreenath, Tabuada, *ECC*'19



The Barrier Certificate

$$\dot{h}(x,u) \geq -\alpha(h(x))$$

$$\nabla h(x)^T (f(x) + g(x)u)) \geq -\alpha(h(x))$$

$$\nabla h(x)^T g(x)u \geq -\nabla h(x)^T f(x) - \alpha(h(x))$$

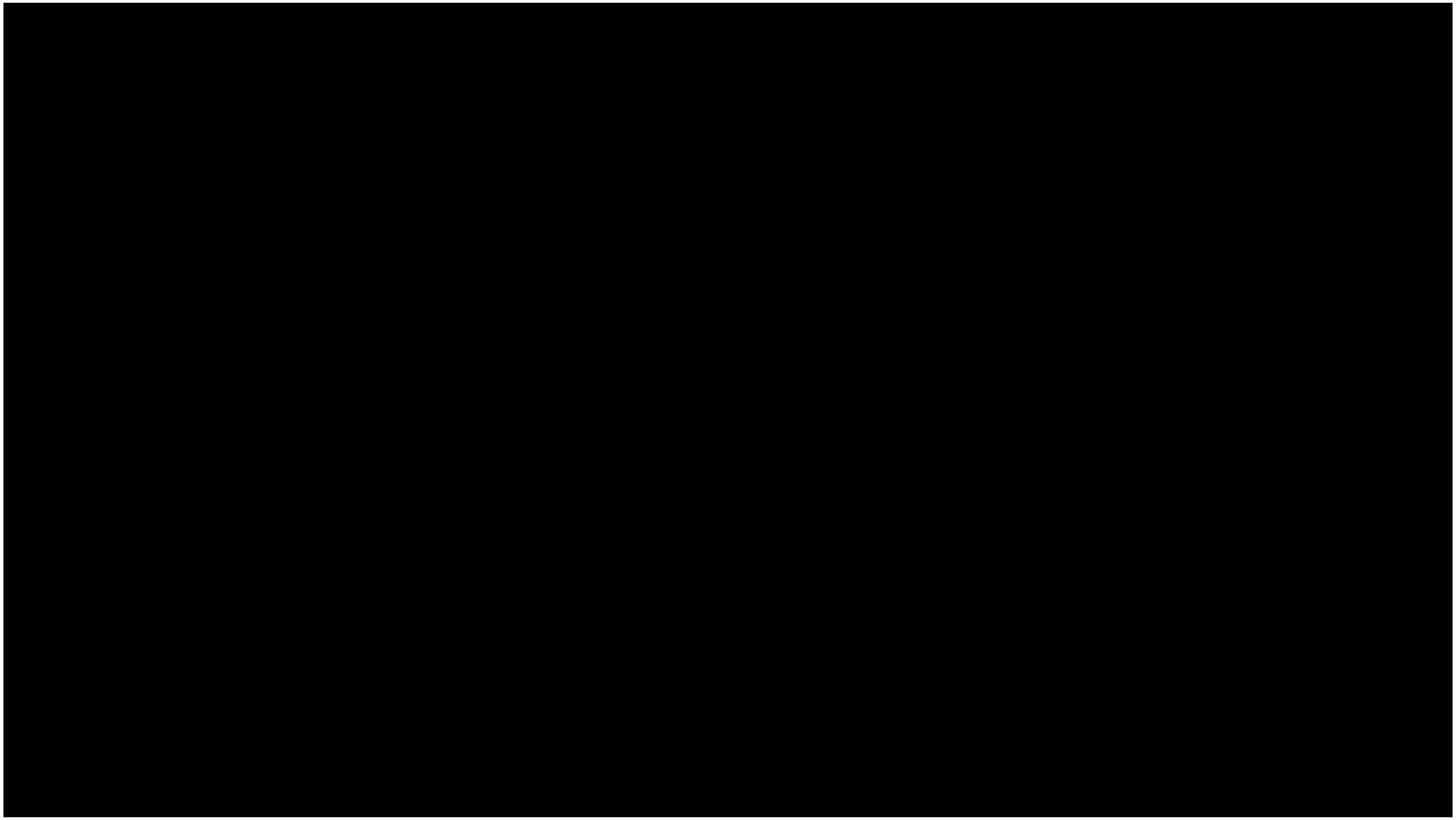
$$\mathcal{A}(x)\mathbf{u} \geq \mathcal{B}(x)$$

$$\min_{\mathbf{u}} \|\mathbf{u} - u_n\|^2 \quad \textbf{QP!}$$
$$\text{s.t. } \mathcal{A}(x)\mathbf{u} \geq \mathcal{B}(x)$$

If the input satisfies the constraint, then, if the system starts safe, it stays safe.

Wang, Ames, Egerstedt, *TRO*'17; Emam, Glotfelter, Wilson, Notomista, Egerstedt, *TRO*'22

Constraint-Based Collision Avoidance



Wang, Ames, Egerstedt, *TRO*'17. Emam, Glotfelter, Wilson, Notomista, Egerstedt, *TRO*'22.

And In the Air

Wang, Ames, Egerstedt, *ICRA*'17

Example: Safe Learning

Wang, Theodorou, Egerstedt, *ICRA*'18, *ICRA*'20

The Route

I. Long Duration Autonomy

ROBOTARIUM

II. Swarm Robotics

III. Robot Ecology

"Short-Duration" Swarm Robotics





Ji, Egerstedt, TRO'07

Barrier to entry:

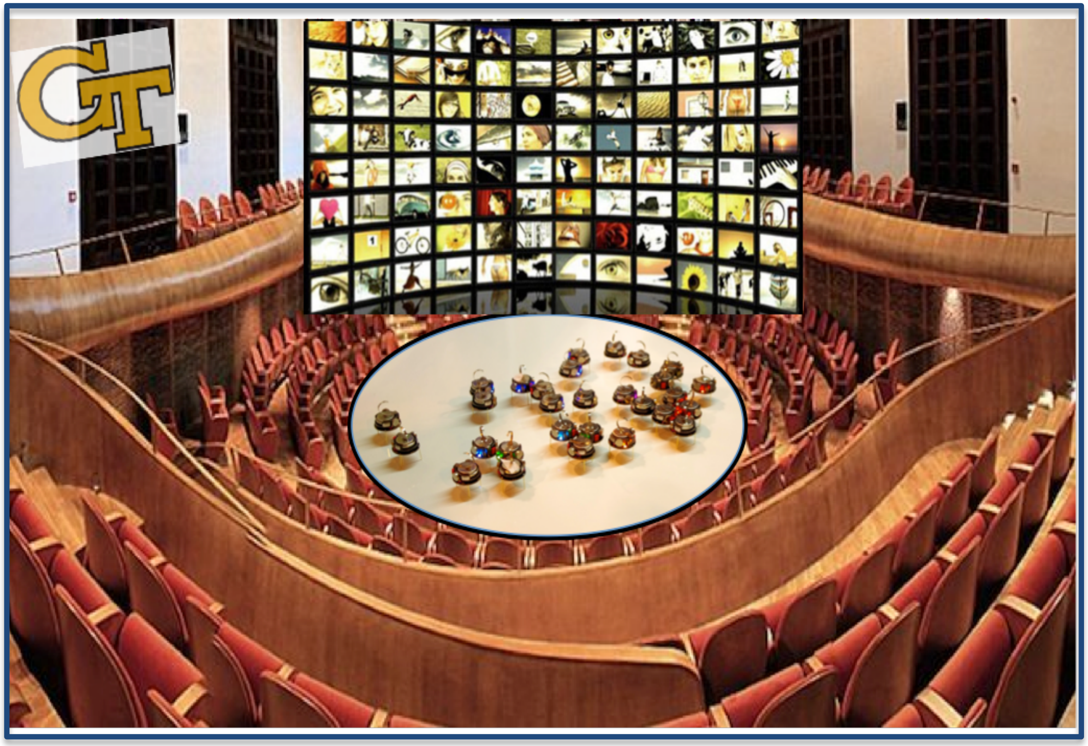
- Resource intense

Speedbumps:

- Duplication of effort
- Underutilized labs
- Hard to compare, leverage, and collaborate

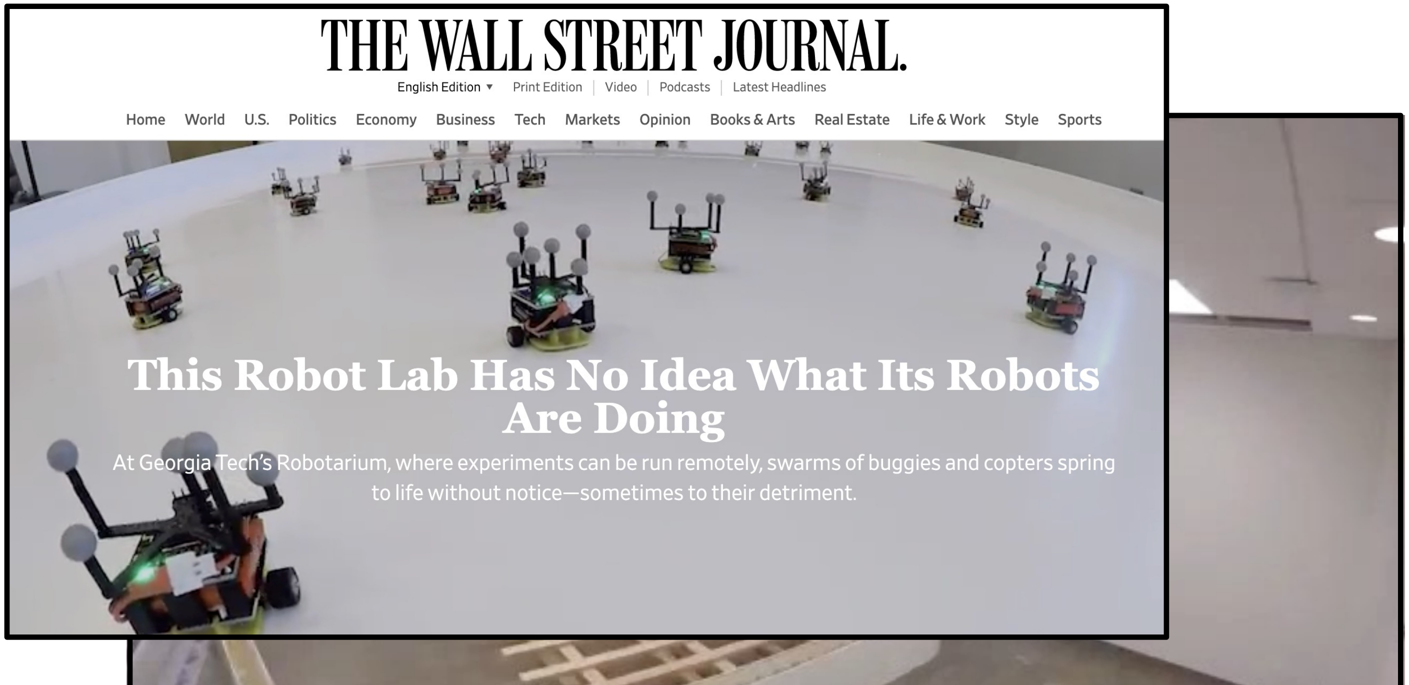
The Robotarium

Vision: An open, remote-access swarm-robotics testbed!



Robotarium: A Shared, Remote-Access Multi-Robot Laboratory

The Robotarium



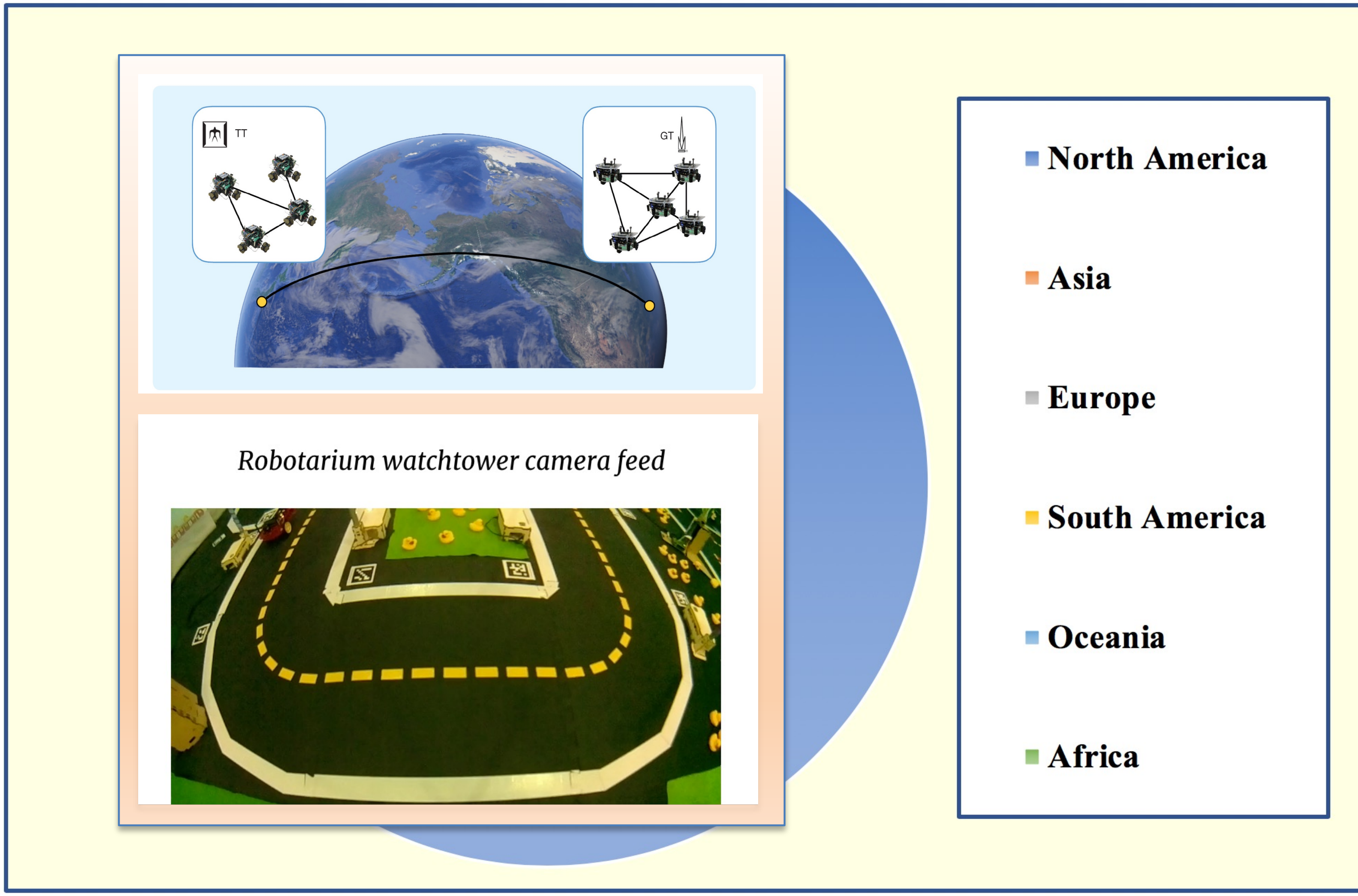
minimize: “**distance**” between actual input and user specified input
subject to: always stay “**safe**”

Pickem, Glotfelter, Wang, Mote, Ames, Feron, Egerstedt, *ICRA*’17
Wilson, Glotfelter, Mayya, Notomista, Emam, Cai, Egerstedt, *RAL*’21

Robotarium With Safety

Wilson, Glotfelter, Mayya, Notomista, Emam, Cai, Egerstedt, *RAL'*21

Since Aug. 2017: 700+ Labs, 4500+ Users, 7500+ Experiments, 250+ Papers



Wilson, Glotfelter, Wang, Mayya, Notomista, Mote, Egerstedt, *CSM*'20

Collaborative Interactions Through Constraints

state: x_i

barrier function: $h_i(x_i)$

safe set:

$$S_i = \{x_i \mid h_i(x_i) \geq 0\} \subset \mathcal{X}_i$$

$$H_i(x) = \bigoplus_{j=1}^{N} h_{ij}(x_i, x_j)$$

pairwise impact: $h_{ij}(x_i, x_j)$

composition:

$$H_i(x_i, x_j) = h_i(x_i) \oplus h_{ij}(x_i, x_j)$$

individual (potentially) safe set:

$$S_{ij} = \{x_i \mid \exists x_j \text{ s.t. } H_i(x_i, x_j) \geq 0\} \subset \mathcal{X}_i$$

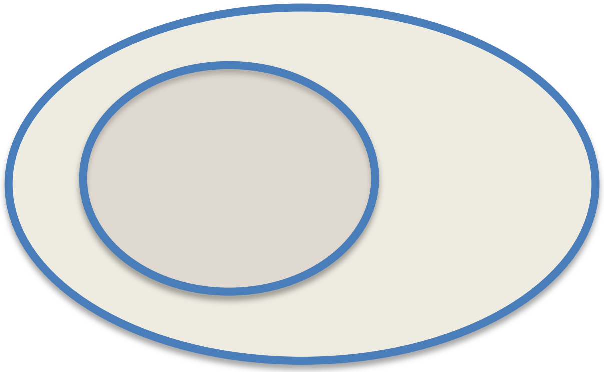
Nguyen, Jabbari, Egerstedt, *CDC*'23

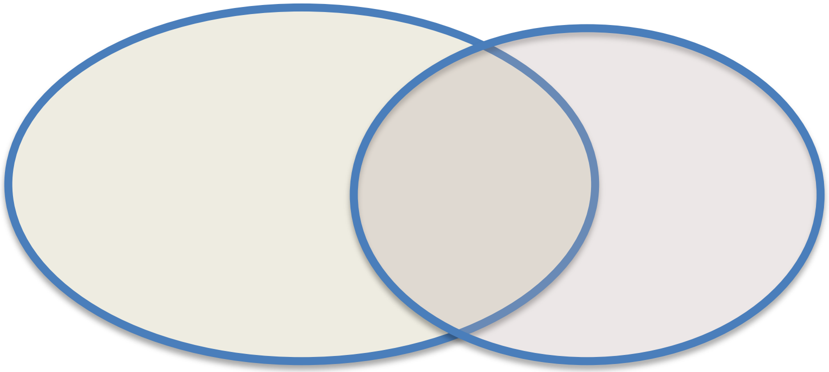
Pairwise Potential for Collaboration

$S_i \subset S_{ij}$ collaboration is (potentially) beneficial

$S_{ij} \subset S_i$ collaboration is (for sure) detrimental

$S_i \not\subset S_{ij} \wedge S_{ij} \not\subset S_i$ unclear



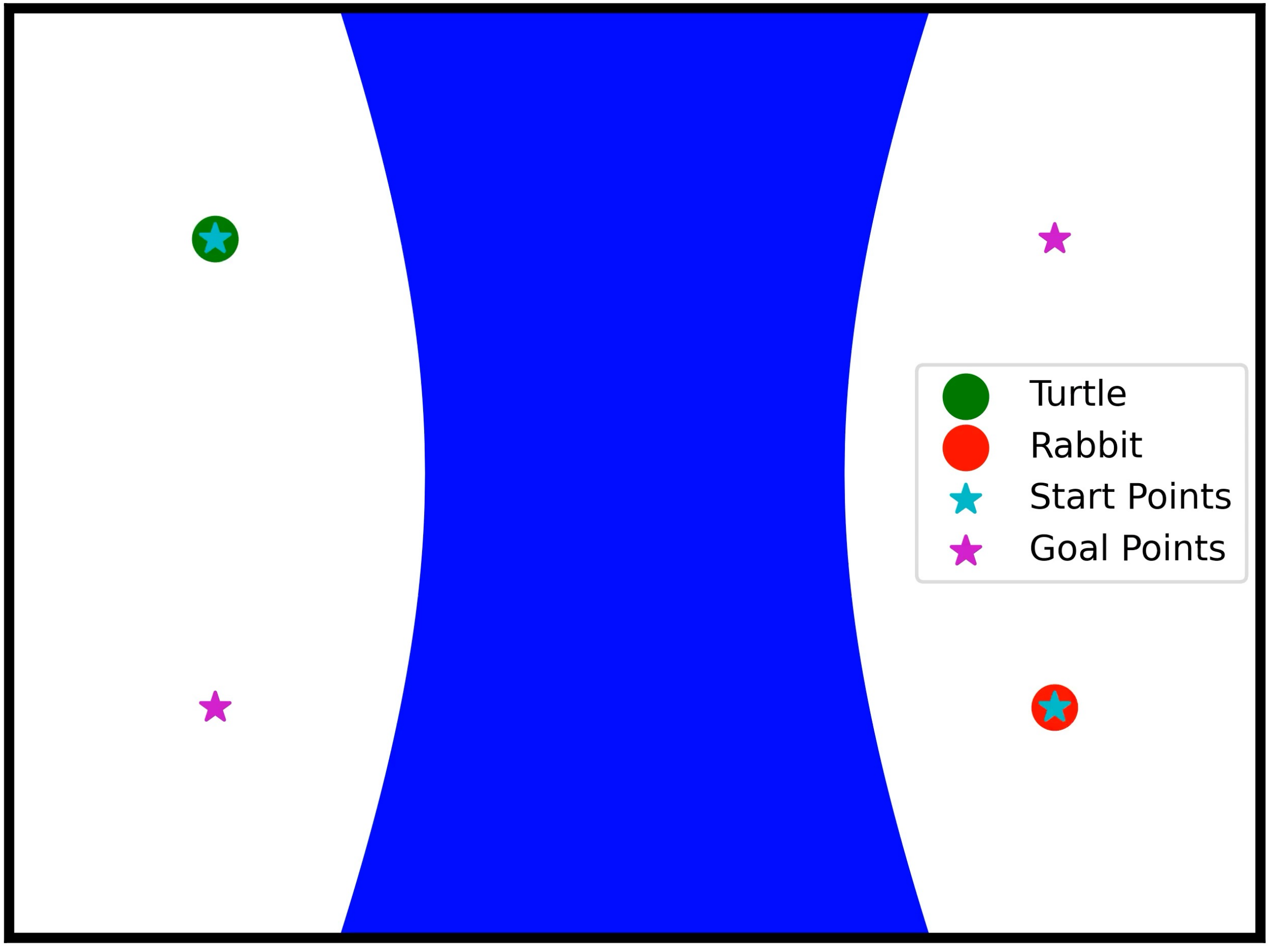


(potential for) **mutualism**

$$S_i \subset S_{ij} \wedge S_j \subset S_{ji}$$

Nguyen, Jabbari, Egerstedt, *CDC*'23

Turtles and Rabbits



Nguyen, Jabbari, Egerstedt, *CDC*'23

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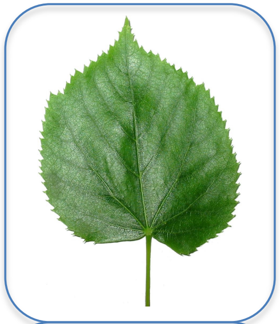
From How to What?

An Ecological Detour



"*Biological diversity and richness of behavior are largely driven by constraints*"
– Jon Pauli, Univ. Wisconsin, Madison

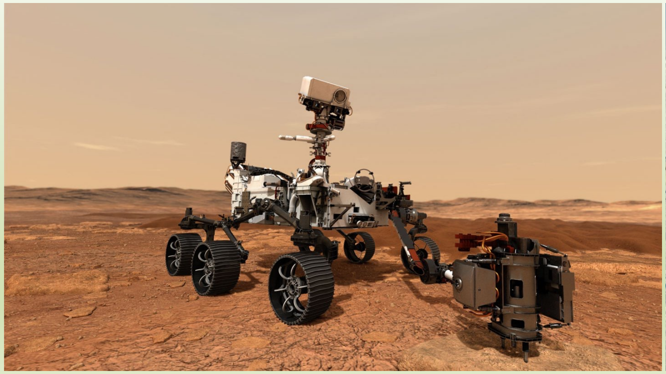
minimize: **energy expenditures**
subject to: **don't die**

An Ecological Detour

minimize: **energy expenditures**
subject to: **don't die**

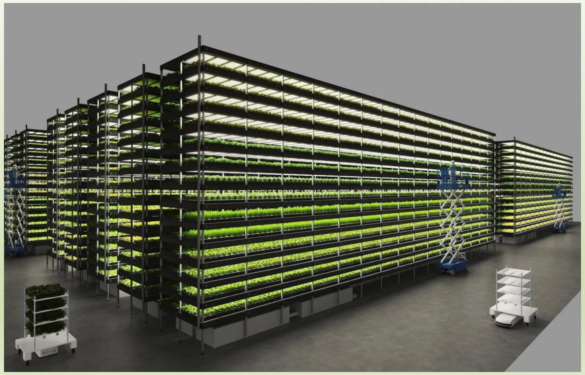
Robots in the Wild

Environmental Monitoring



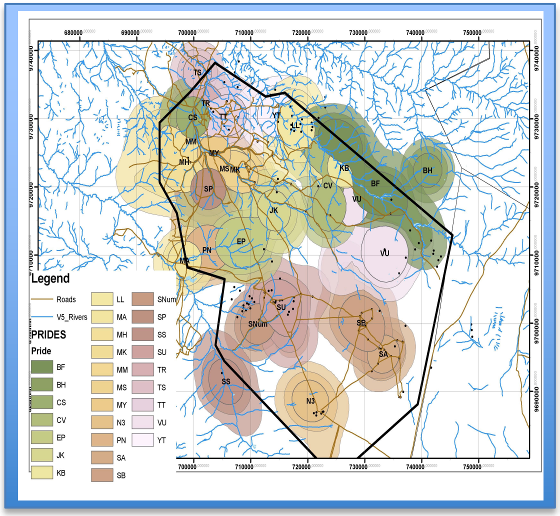
Precision Agriculture





Environmental Monitoring

Hamilton, 1971. Hedrick, Liu, Garvey, 2011. Packer, Gilbert, Pusey, O'Brien 1991.



minimize: **energy expenditures**
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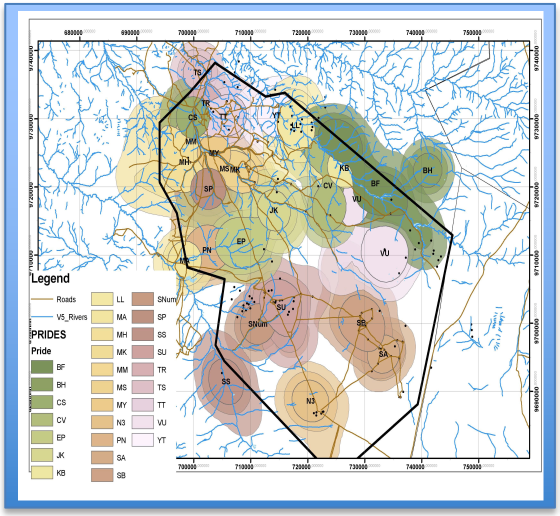


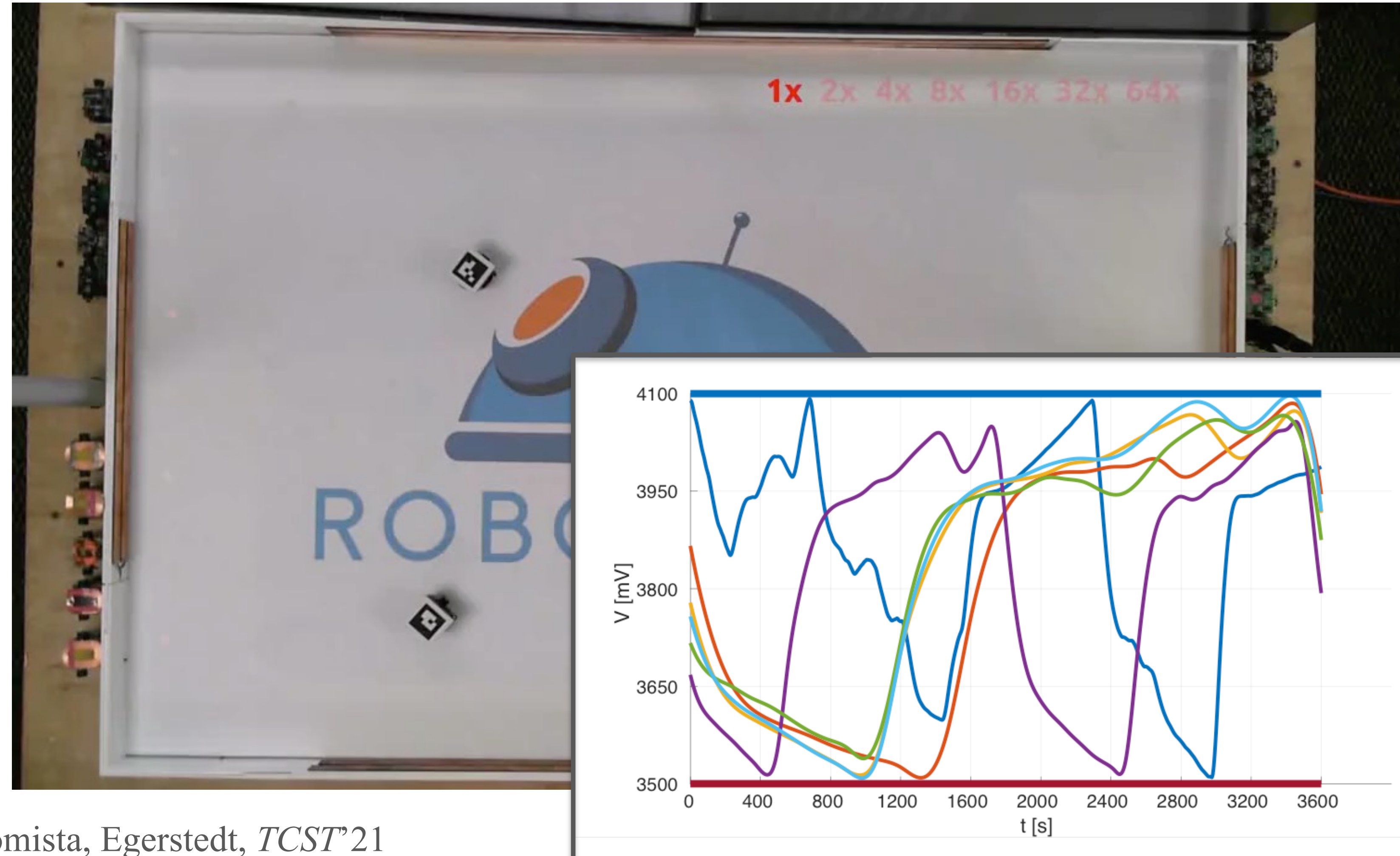
Egerstedt, Pauli, Notomista, Hutchinson, *ARC*'18

minimize: **energy expenditures**

subject to: **don't die**

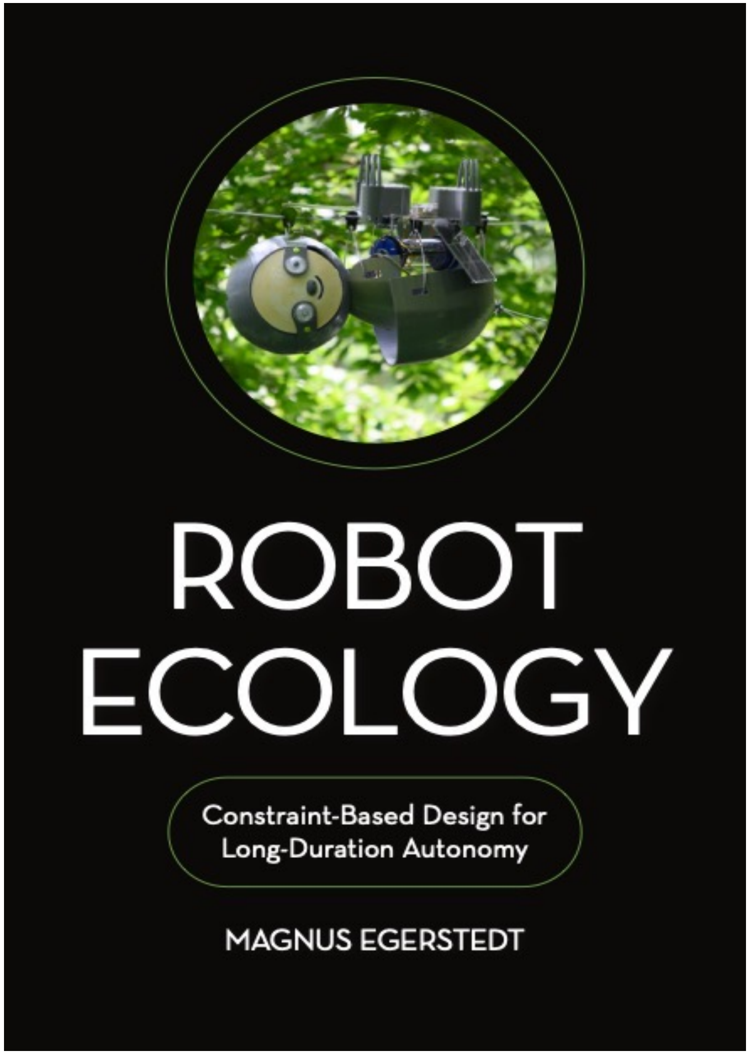
= **don't collide and always have enough power to return to a charging station and cover a sufficiently big area or charge the batteries**

Robots That Do Nothing Most of the Time



Notomista, Egerstedt, *TCST*'21

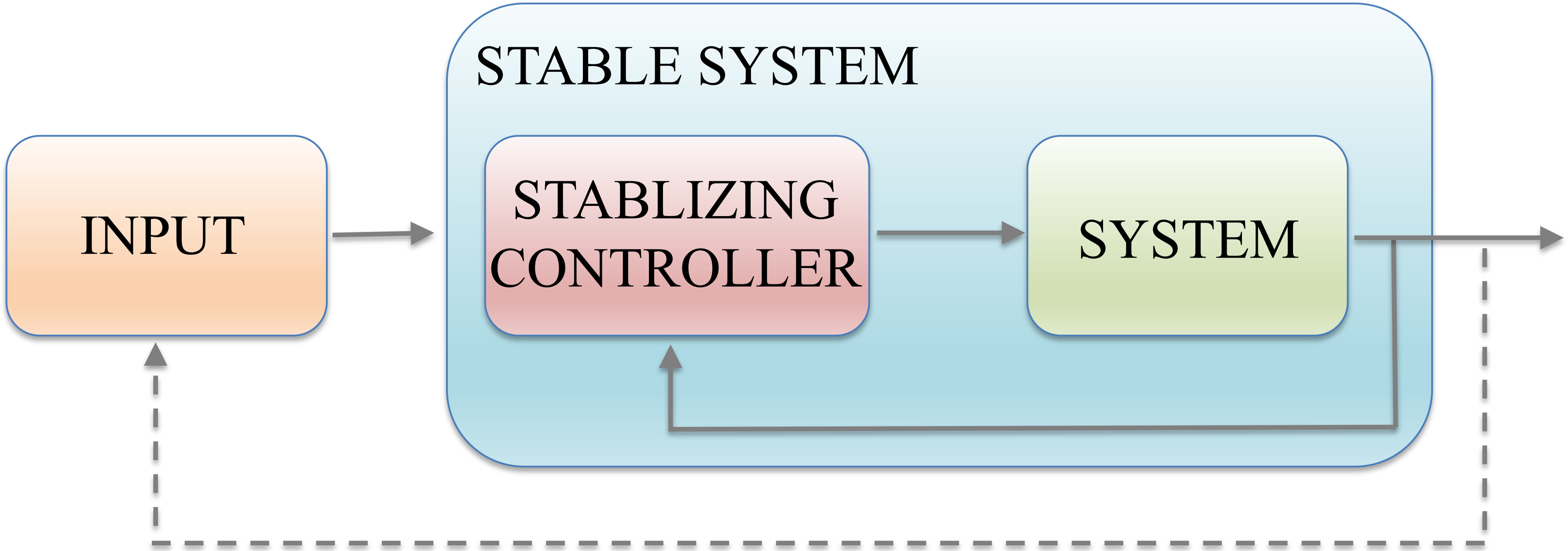
Robot Ecology



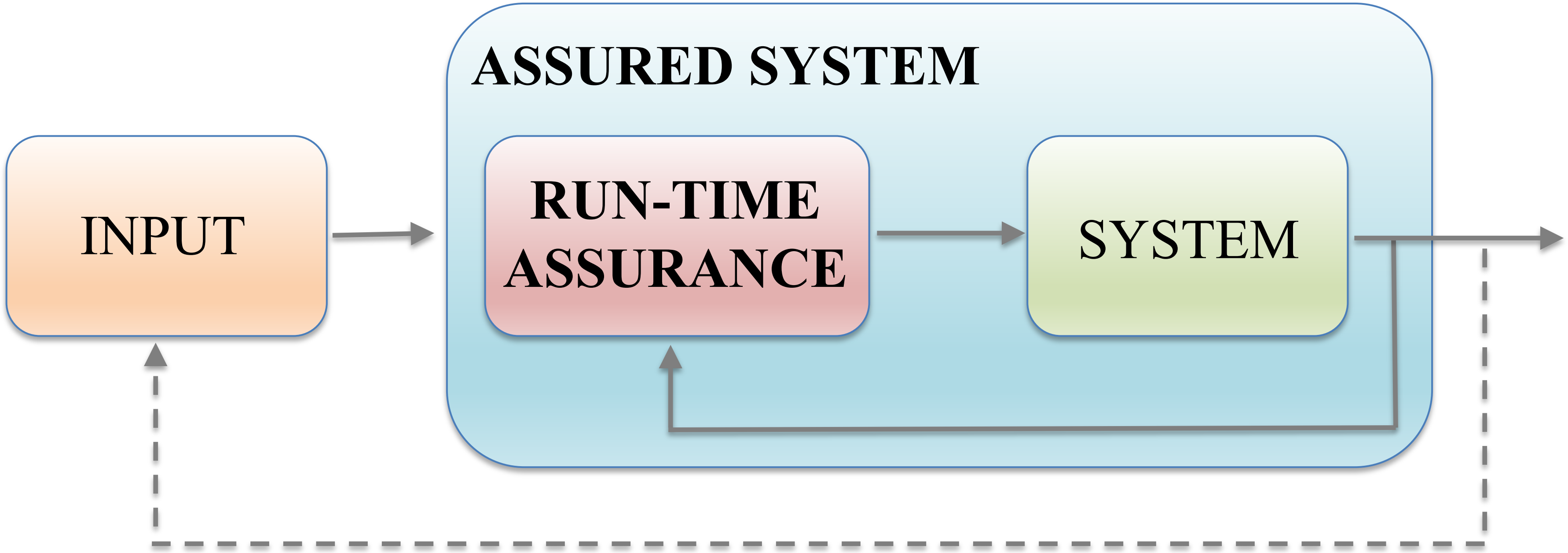
The SlothBot

Egerstedt, *PUP*'21.
Notomista, Emam, Egerstedt, *RAL'*21.

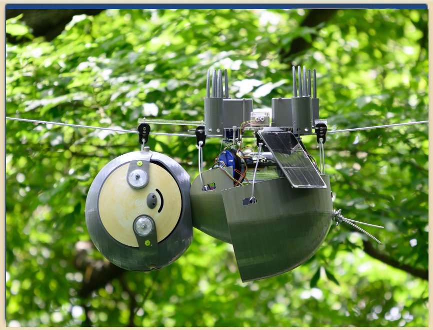
Assured Autonomy

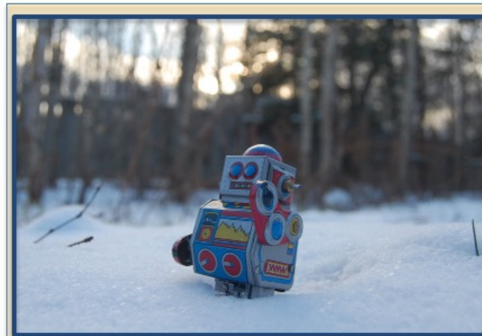


Assured Autonomy



THANKS!





Lab members: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P. Glotfelter


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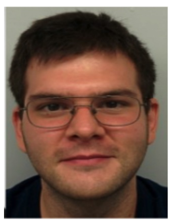
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