Design of robotic swarms for long-term environmental monitoring

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Long-duration robot autonomy

Robots deployed over *long time horizons*

   

Long-duration robot autonomy

Robots deployed over *long time horizons*




- We need the **synergistic combination of robot design and control**
- Main application: **Environmental monitoring for climate change ecology**

The SlothBot

Constraint-based control paradigm

- Energy awareness
- Resilience

Scaling up robot environmental monitoring

The SlothBot

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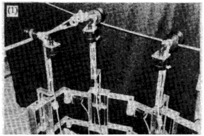
Scaling up robot environmental monitoring

The SlothBot

Robots for long-term deployment

- UAVs
- UGVs
- USVs
- Wire-traversing robots



Pouliot, Montambault, *Geometric design of the LineScout, a teleoperated robot for power line inspection and maintenance*, ICRA 2008

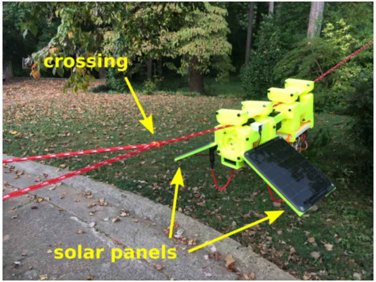
Cho et al., *Caterpillar-based cable climbing robot for inspection of suspension bridge hanger rope*, CASE 2013

Morozovsky, Bewley, *SkySweeper: A low DOF, dynamic high wire robot*, IROS 2013

Debenest et al., *Expliner - Robot for inspection of transmission lines*, ICRA 2008

Aoshima, Tsujimura, Yabuta, *A wire mobile robot with multi-unit structure*, IROS 1989

The SlothBot (v1)



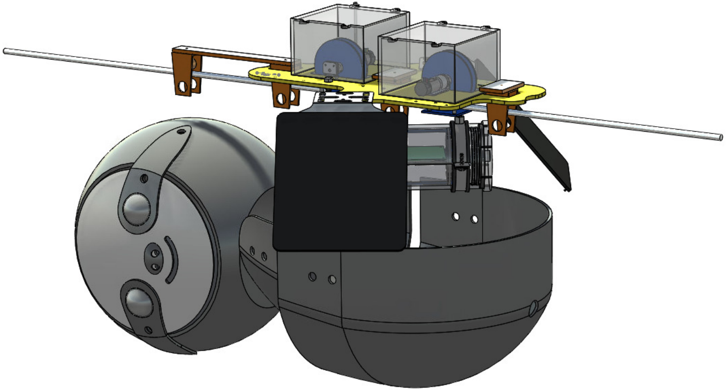
	Locomotion	Wire-Switch	Fail-safe	# Actuators	Weight (Kg)
LineScout	Wheels	No	Yes	—	100
Caterpillar-like robot	Wheels	No	Yes	—	—
SkySweeper	Pulley Arms	No	Yes	3	0.466
Expliner	Wheels	Yes	No	6	60
Modular robot	Wheels	Yes	Yes	16	10
SlothBot[22]	Wheels	Yes	Yes	7	1

G. Notomista, Y. Emam, and M. Egerstedt, The SlothBot: A novel design for a wire-traversing robot, *IEEE Robotics and Automation Letters, Vol. 4, No. 2, pp. 1993-1998, 2019*

The SlothBot (v1)

The SlothBot (v2)

The SlothBot (v3)



The SlothBot (v3)

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Components description

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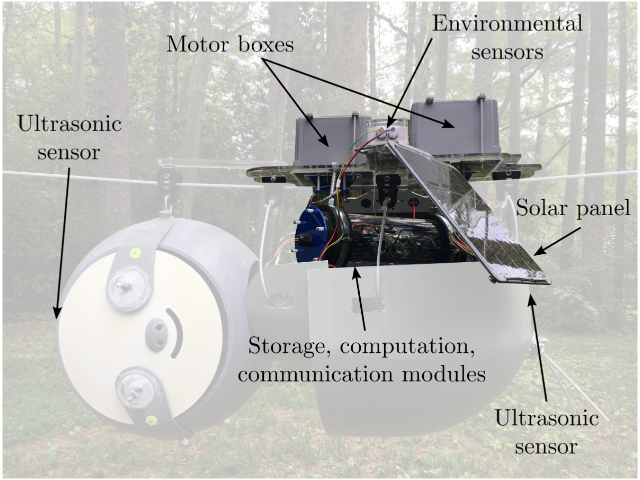
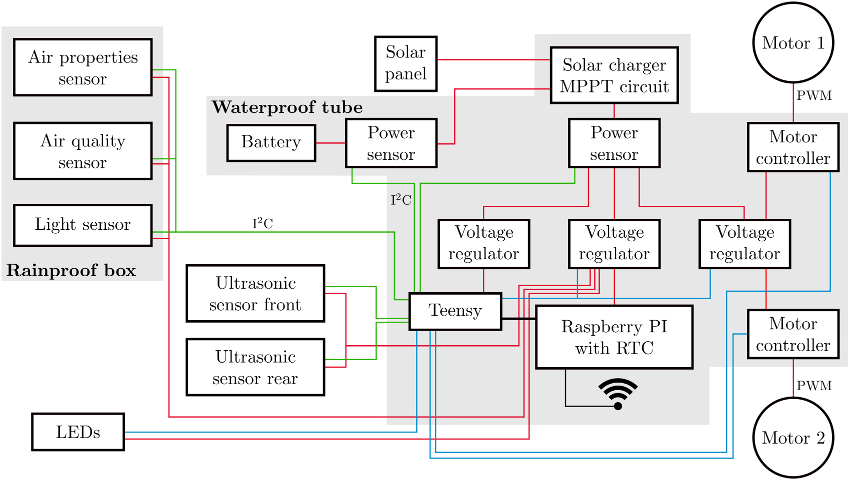
Components description



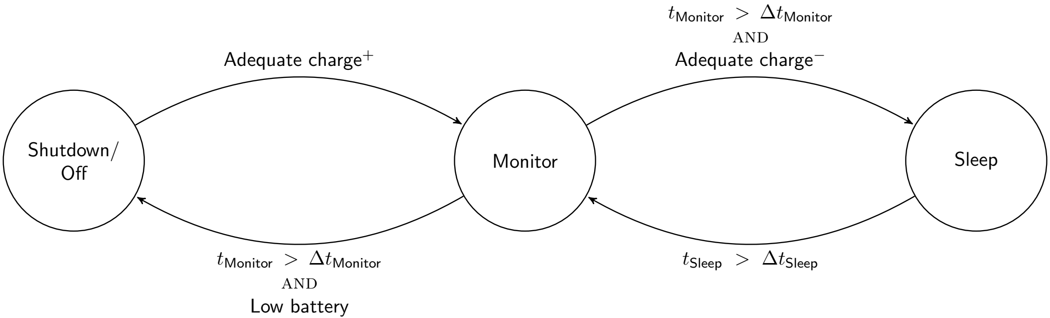
The SlothBot (v3)

Hardware architecture



The SlothBot (v3)

High-level software architecture



The SlothBot

Constraint-based control paradigm

Energy awareness

Resilience

Scaling up robot environmental monitoring

A sloth

Towards robot ecology

Ecological studies have shown that behaviors are determined by ecological constraints, not by objectives.

A slothbot

Advantage of constraints over objectives

$\nexists$ right way of combining objectives: **Sum? Multiply?**
$\exists!$ way of combining constraints: **Enforce them all!**

1 task

$$\begin{aligned} \underset{u}{\text{minimize}}\ & \|u\|^2 \\ \text{subject to}\ & c_{\text{task}}(x,u) \leq 0 \end{aligned}$$

where

- $x \in \mathbb{R}^n$ is the state of the robot
- $u \in \mathbb{R}^m$ is the control effort $\propto$ **energy spent (optimization variable)**
- $c_{\text{task}} : \mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}$ encodes the task **e.g. multi-robot environmental monitoring**

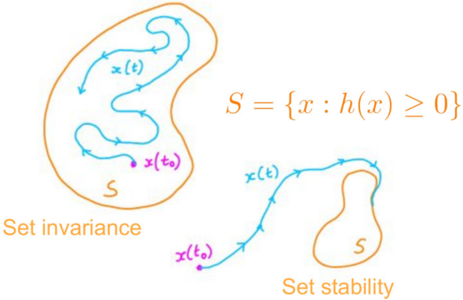
N tasks

$$\begin{aligned} \underset{u}{\text{minimize}} \ & \|u\|^2 \\ \text{subject to } & c_{\text{task},1}(x,u) \leq 0 \\ & \vdots \\ & c_{\text{task},N}(x,u) \leq 0 \end{aligned}$$

where, for the multi-robot environmental monitoring task,

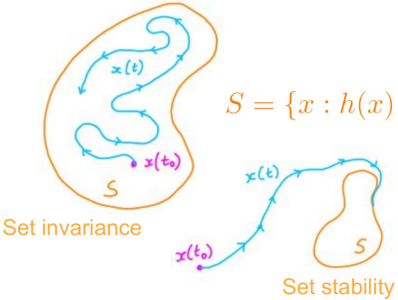
- $c_{\text{task},1}(x,u) \leq 0$ may encode data collection
- $c_{\text{task},2}(x,u) \leq 0$ may encode data communication
- $c_{\text{task},3}(x,u) \leq 0$ may encode data processing

How do we represent tasks as constraints?

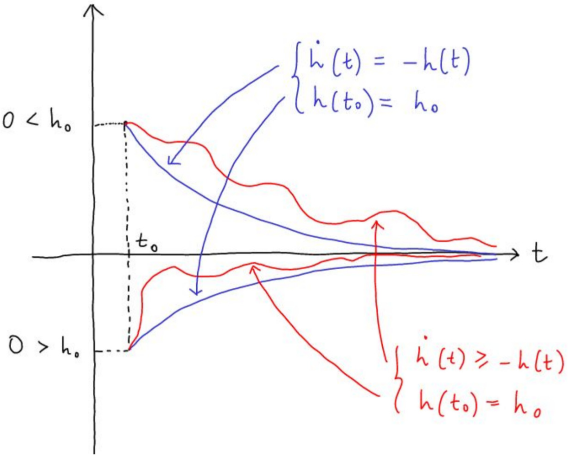


$$S = \{x : h(x) \geq 0\}$$

How do we represent tasks as constraints?



$S = \{x : h(x) \geq 0\}$



How do we represent tasks as constraints?

Given a robot model $\dot{x} = f(x) + g(x)u$, we consider tasks that can be executed by rendering a set **asymptotically stable** or **forward invariant**.

From state to input constraints

This is achieved by enforcing the following constraint on u:

$$c_{\text{task},i}(x, u) := -L_f h_i(x) - L_g h_i(x) u - \alpha(h_i(x)) \leq 0,$$

where h_i is a *control barrier function* associated with task i and $\alpha \in \mathcal{K}$.

A. D. Ames, S. Coogan, M. Egerstedt, G. Notomista, K. Sreenath, and P. Tabuada, Control barrier functions: Theory and applications, in *2019 18th European Control Conference (ECC)*. IEEE, 2019, pp. 3420–3431

The SlothBot

Constraint-based control paradigm

Energy awareness

Resilience

Scaling up robot environmental monitoring

Energy control as forward invariance

Define the following control barrier function:

$$h_e(x) := e - e_{\min} - \rho(\|p(x) - p_c\|),$$

where

- e is the robot energy
- $e_{\min}$ is a lower bound on the robot energy (design parameter)
- $\rho(\|p(x) - p_c\|)$ is an upper bound on the energy required to reach a charging station located at p_c starting from $p(x)$

$$h_e(x) \geq 0$$

$$\Leftrightarrow$$

The robot will reach the charging station before its energy goes below the lower bound

G. Notomista and M. Egerstedt, "Persistification of robotic tasks," *Transactions on Control Systems Technology*, 2020.

Energy control as forward invariance

$$\begin{aligned} \underset{u}{\text{minimize}} \ & \|u\|^2 \\ \text{subject to} \ & -L_f h_1(x) - L_g h_1(x)u - \alpha(h_1(x))\big) \leq 0 \quad \longleftarrow \text{task constraint} \\ & \vdots \\ & -L_f h_N(x) - L_g h_N(x)u - \alpha(h_N(x))\big) \leq 0 \quad \longleftarrow \text{task constraint} \\ & -L_f h_e(x) - L_g h_e(x)u - \alpha(h_e(x)) \leq 0 \quad \longleftarrow \text{energy constraint} \end{aligned}$$

G. Notomista and M. Egerstedt, Constraint-driven coordinated control of multi-robot systems, in *2019 American Control Conference (ACC)*. IEEE, 2019, pp. 1990–1996

G. Notomista, A Constrained-Optimization Approach to the Execution of Prioritized Stacks of Learned Multi-Robot Tasks, in *International Symposium on Distributed Autonomous Robotic Systems*, 2022

Energy control as forward invariance

$$\begin{aligned}
&\underset{u}{\text{minimize}}\ \|u\|^2 \\
&\text{subject to}\ -L_f h_1(x) - L_g h_1(x)u - \alpha(h_1(x)) \le 0 \quad \longleftarrow \text{task constraint} \\
&\qquad\qquad \vdots \\
&\qquad -L_f h_N(x) - L_g h_N(x)u - \alpha(h_N(x)) \le 0 \quad \longleftarrow \text{task constraint} \\
&\qquad -L_f h_e(x) - L_g h_e(x)u - \alpha(h_e(x)) \le 0 \quad \longleftarrow \text{energy constraint}
\end{aligned}$$

- Feasibility?
- Stability?
- **Robustness / resilience?**
- What kinds of tasks can we execute with this formulation?

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The SlothBot

Constraint-based control paradigm

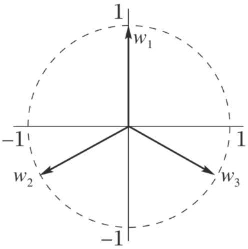
- Energy awareness
- Resilience

Scaling up robot environmental monitoring

Resilience

Ability of a system to recover from failure by altering its behavior and/or its objective

Resilience for constraint-driven-controlled multi-robot systems using *frame theory*



G. Nootmista, "Resilience and Energy-Awareness in Constraint-Driven-Controlled Multi-Robot Systems", in *2022 American control conference (ACC)*. IEEE, 2022, pp. 3682-3687

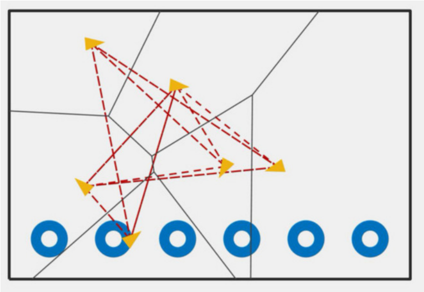
Resilience

$$
\begin{aligned}
\underset{u}{\text{minimize}} \ & \|u\|^2 \\
\text{subject to} \ & -L_f h_1(x) - L_g h_1(x)u - \alpha(h_1(x))\big) \leq 0 \quad \longleftarrow \text{task constraint} \\
& \vdots \\
& -L_f h_N(x) - L_g h_N(x)u - \alpha(h_N(x))\big) \leq 0 \quad \longleftarrow \text{task constraint} \\
& -L_f h_e(x) - L_g h_e(x)u - \alpha(h_e(x)) \leq 0 \quad \longleftarrow \text{energy constraint} \\
& -L_f h_r(x) - L_g h_r(x)u - \alpha(h_r(x)) \leq 0 \quad \longleftarrow \text{resilience constraint}
\end{aligned}
$$

G. Nootmista, "Resilience and Energy-Awareness in Constraint-Driven-Controlled Multi-Robot Systems", in *2022 American control conference (ACC)*. IEEE, 2022, pp. 3682-3687

Resilience: simulation results

- 6 robots
- 2 tasks
  - Coverage control
  - Formation control
- 6 charging stations
- Failures
  - One robot breaks at time 180s
  - Another robot breaks at time 240s



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Resilience: simulation results

Without resilience constraint

With resilience constraint

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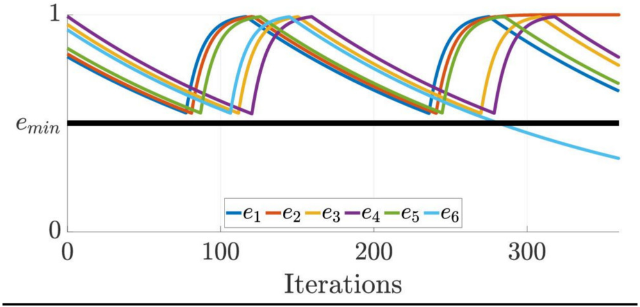
Resilience: simulation results



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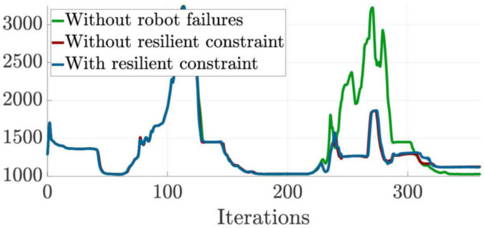
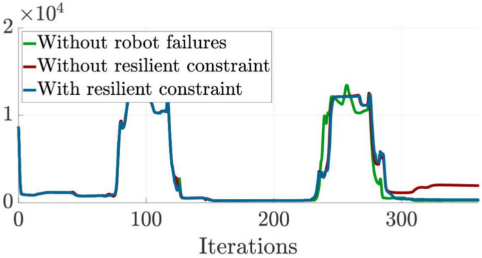
Resilience: simulation results

Coverage control task CBF (absolute value)



Formation control task CBF (absolute value)



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Scaling up robot environmental monitoring

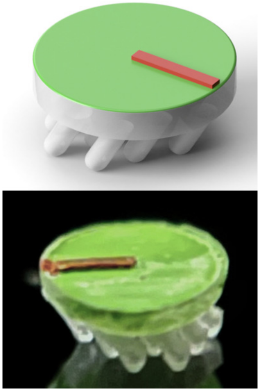
The power of swarms

- Design simplicity
- Energy efficiency
- Resilience

Outsourcing computation, communication, sensing, and locomotion

Z. Hao, S. Mayya, G. Notomista, S. Hutchinson, M. Egerstedt, and A. Ansari, "Controlling Collision-Induced Aggregations in a Swarm of Micro Bristle-Robots", *IEEE Transactions on Robotics*, 2022

Outsourcing computation, communication, sensing, and locomotion



Z. Hao, S. Mayya, G. Notomista, S. Hutchinson, M. Egerstedt, and A. Ansari, "Controlling Collision-Induced Aggregations in a Swarm of Micro Bristle-Robots", *IEEE Transactions on Robotics*, 2022

ERABLab

Ecological and Resilient Autonomous roBots Laboratory

Research themes

- Ecological robot design (biodegradable mechanics and electronics)
- Resilient robotic systems (design and control)
- Human-multi-robot interaction (intuitiveness and safety)
- Main application: **Environmental monitoring for climate change ecology**

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