Compositional Robotics Workshop
ICRA 2021, May 31, Xi’An, China

Toward Practicable Hybrid Dynamical Type Theories for Programming Physical Robot Behaviors

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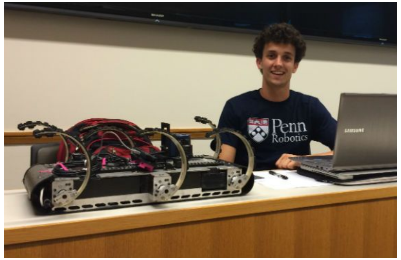
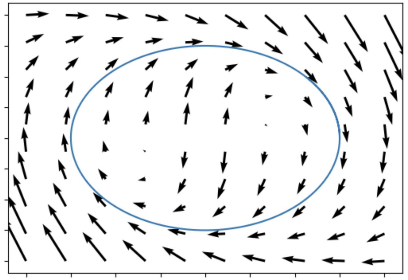
Can we make behaviors modular?

Current approach:
Grad student descent



The future:
Physically-grounded programming languages



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English	Type Theory
True	$\mathbf{1}$
False	$\mathbf{0}$
A and B	$A \times B$
A or B	$A + B$
If A then B	$A \to B$
A if and only if B	$(A \to B) \times (B \to A)$
Not A	$A \to \mathbf{0}$

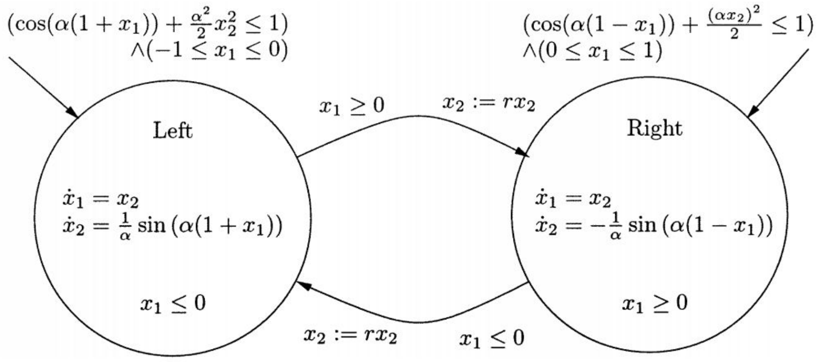
Big Picture

- Composition invariably leads to **categories** (either explicit or implicit)
  - Interfaces <-> objects <-> types
  - Controllers <-> morphisms <-> terms
- How can we encode **parallel**, **hierarchical**, and **sequential compositions** of hybrid systems?
- How can we incorporate **liveness** and **safety** constraints?
- How can we develop **interoperability** with the state-of-the-art linear-time temporal logic (LTL)-based synthesis approaches?

Hybrid systems and semiconjugacies

A **hybrid system** H consists of

- a directed graph $G = (V, E, \mathfrak{s}, \mathfrak{t})$;
- for each **mode** $v \in V$,
  - an **ambient smooth system** (M_v, X_v)
  - an **active set** $I_v \subset M_v$
  - a **flow set** $F_v \subset I_v$
- for each **reset** $e \in E$, a **guard set** $Z_e \subset I_{\mathfrak{s}(e)}$ and an associated **reset map** $r_e \colon Z_e \to I_{\mathfrak{t}(e)}$.



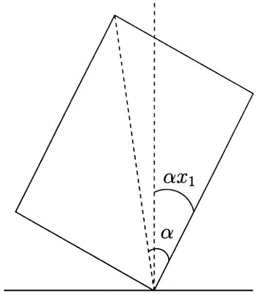
Morphisms: hybrid semiconjugacies

- "execution-preserving maps"

Independent parallel composition

⇕

Categorical product

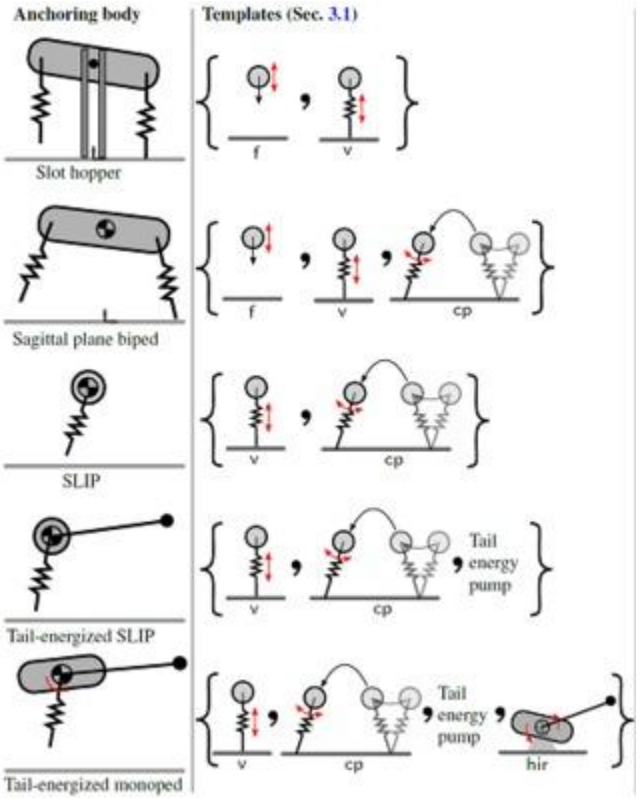


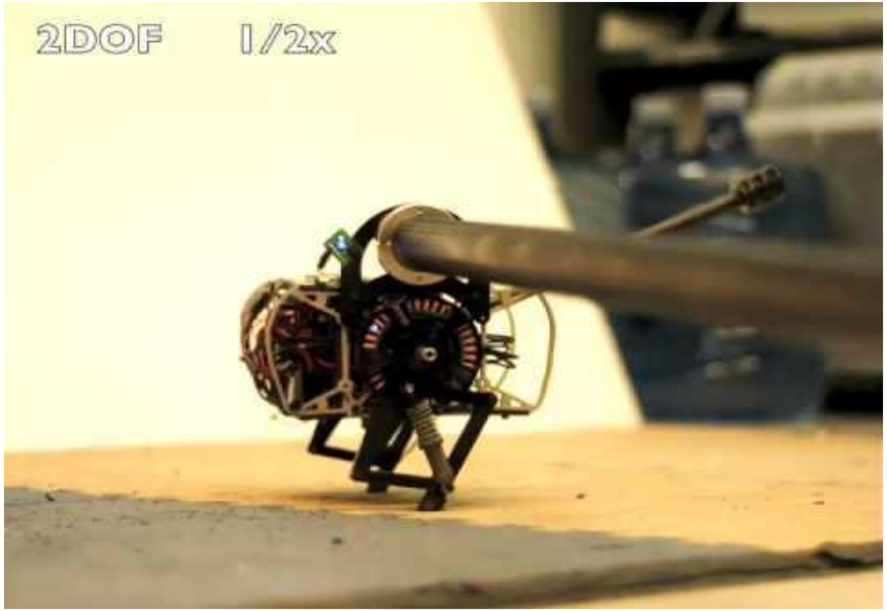
Related work:

- **Lerman**. "A category of hybrid systems." arXiv:1612.01950, 2016.
- **Ames**. "A Categorical Theory of Hybrid Systems." PhD dissertation, Electrical Engineering and Computer Sciences, University of California, Berkeley, 2006.

Image source: Lygeros et al., "Dynamical properties of hybrid automata." IEEE Transactions on automatic control, 2003.

Abstraction via templates and anchors



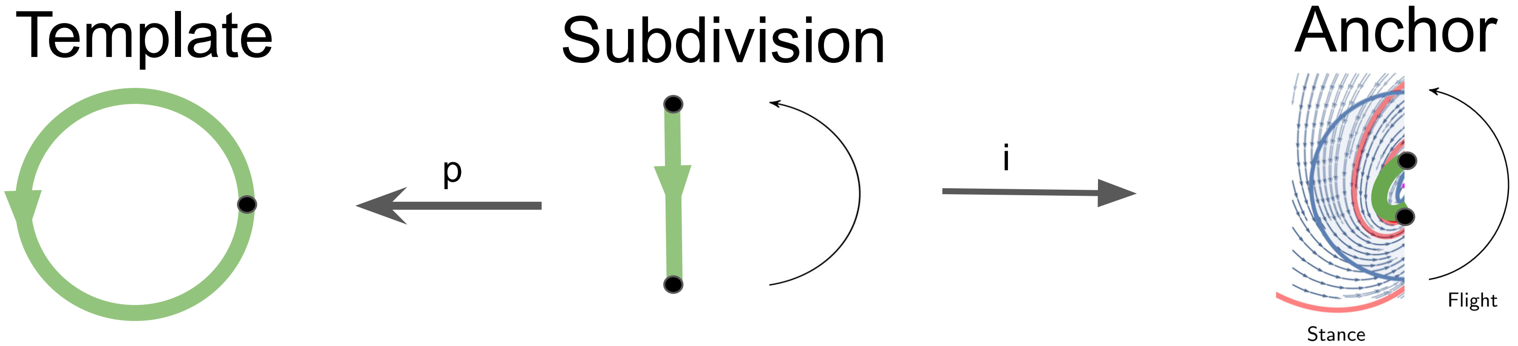


- Full and Koditschek. "Templates and anchors: neuromechanical hypotheses of legged locomotion on land." ***Journal of experimental biology***, 1999.
- De and Koditschek. "Parallel composition of templates for tail-energized planar hopping." **ICRA**, 2015.

Anchoring a limit cycle in a vertical hopper

A **template-anchor pair** is a span $T \xleftarrow{p} S \xrightarrow{i} A$ such that

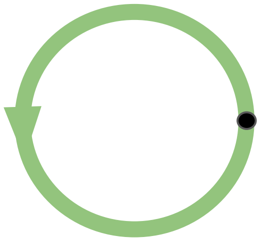
- p is a hybrid subdivision;
- i is a hybrid embedding;
- $i(S)$ is attracting in A.

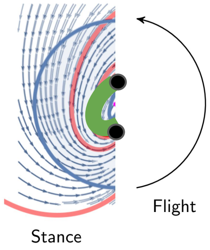


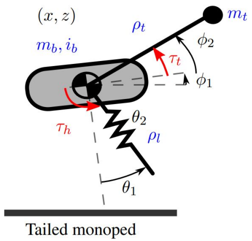
Hierarchical composition

Theorem (CGKS). Template-anchor pairs are weakly associatively composable.

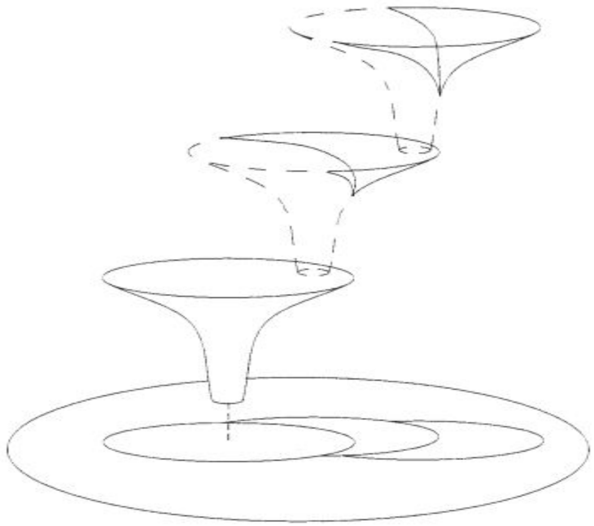
$$
\begin{tikzcd}
& & S = S_1 \times_{A_1} S_2 \arrow[dl, two heads] \arrow[dr, hook] \arrow[ddll, bend right, two heads, "p"'] \arrow[ddrr, bend left, hook, "i"] \arrow[dd, phantom, "\vee", near start] & & \\
& S_1 \arrow[dl, two heads] \arrow[dr, hook] & & S_2 \arrow[dl, two heads] \arrow[dr, hook] & \\
T_1 & & A_1 & & A_2
\end{tikzcd}
$$







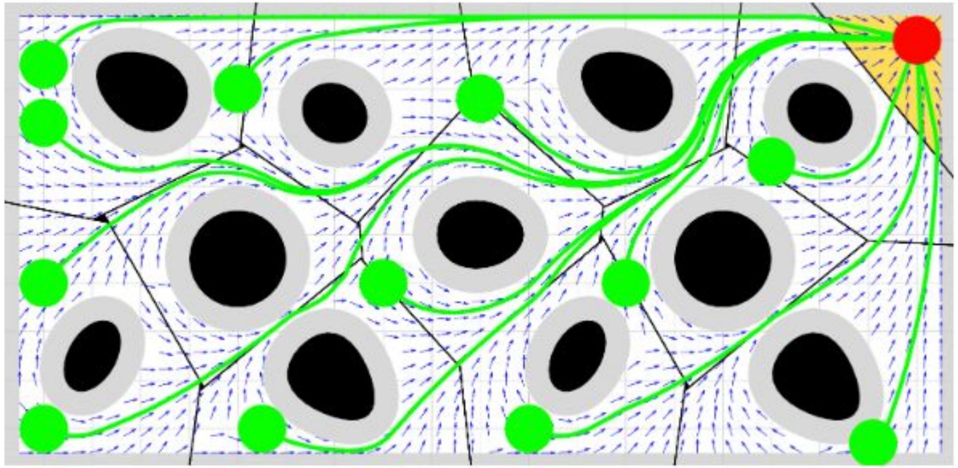
Sequential composition



Burridge, Robert R., Alfred A. Rizzi, and Daniel E. Koditschek. "Sequential composition of dynamically dexterous robot behaviors." *The International Journal of Robotics Research* 18.6 (1999): 534-555.

Goal: define a class of “funnel-like” hybrid systems closed under sequentially composition

Liveness: eventually reach a goal location

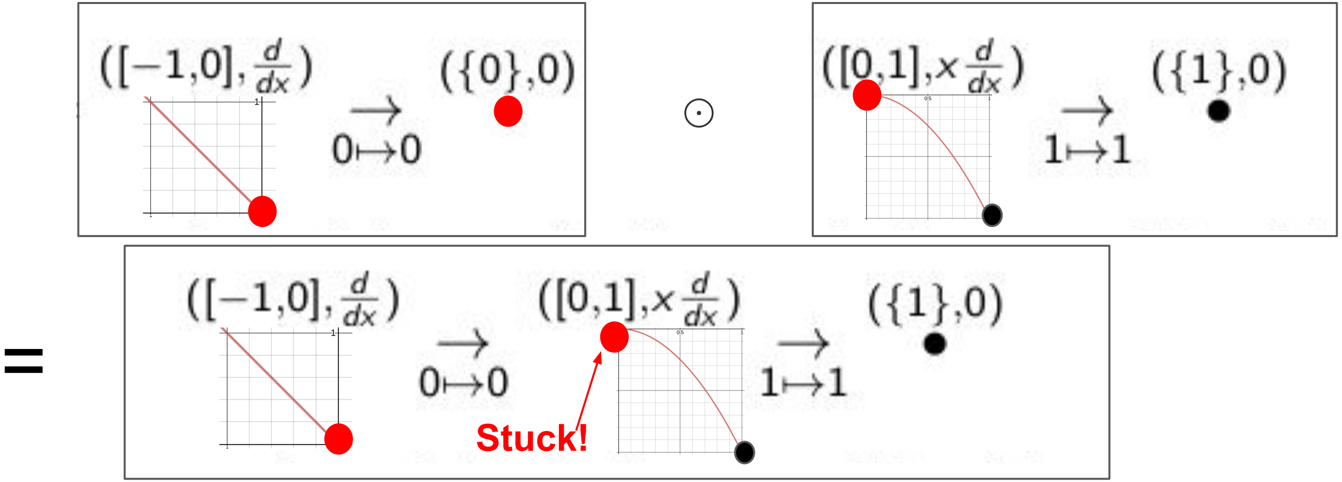


Theorem 3. *The piecewise continuously differentiable "move-to-projected-goal" law in (11) leaves the robot's free space $\mathcal{F}$ (1) positively invariant; and if Assumption 2 holds, then its unique continuously differentiable flow, starting at almost[1] any configuration $\mathrm{x} \in \mathcal{F}$, asymptotically reaches the goal location x^*, while strictly decreasing the squared Euclidean distance to the goal, $\|\mathrm{x} - \mathrm{x}^*\|^2$, along the way.*

Arslan, Omur, and Daniel E. Koditschek. "Sensor-based reactive navigation in unknown convex sphere worlds." *The International Journal of Robotics Research* (2019).

How to define ``funnel-like'' systems?

- **Problem:** the naive measure-theoretic and topologically notions of "almost all" are incompatible with fully general sequential composition
- Example:

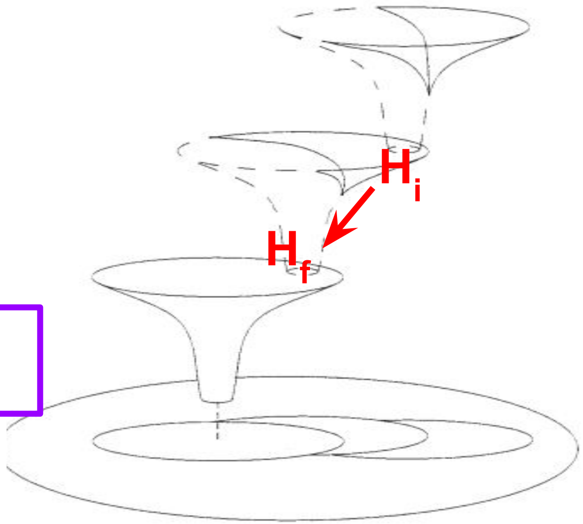


Directed systems

A **directed hybrid system** $H \colon H_i \rightsquigarrow H_f$ is a tuple (H, η_i, η_f) consisting of

- a metric hybrid system H,
- embeddings $\eta_i \colon H_i \to H$ and
- a hybrid embedding $\eta_f \colon H_f \to H$ such that each component $(\eta_f)_v$ is a diffeomorphism, and $G(H_f)$ is a sink in $G(H)$

such that for all $\varepsilon, T > 0$ and $x \in H$, there exists an (ε, T)-**chain** from x to some $y \in H_f$.



Composable!

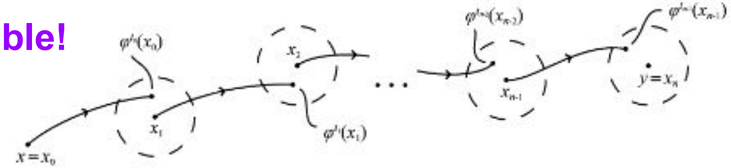
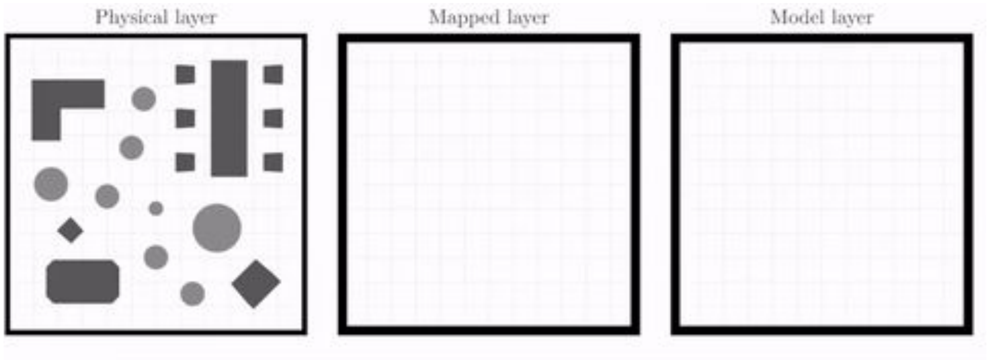


Image source: Alongi and Nelson, *Recurrence and Topology*. AMS, 2007.

A double category of hybrid systems



V. Vasilopoulos, D.E. Koditschek (2018). Reactive Navigation in Partially Known Non-Convex Environments. In WAFR 2018.

Semiconjugacies

$$
\begin{tikzcd}
H_i \arrow[r, "\alpha_i"] \arrow[d, rightsquigarrow, "H"'] \arrow[dr, phantom, "\overset{\alpha}{\Longrightarrow}"] & K_i \arrow[d, rightsquigarrow, "K"] \\
H_f \arrow[r, "\alpha_f"'] & K_f
\end{tikzcd}
$$

Directed systems

Linear dependent type theory

- Dynamic input and output conditions + safety specs
- Linear fragment
  - Manages **states**, **resources**, and **liveness**
  - From symmetric monoidal category of **directed systems** under sequential composition
- Nonlinear fragment
  - Manages sensor-dependent **parameters** and **proofs of safety**
  - Internal language of **presheaves** over the sensorium
    - Example: in this open set of sensor readings, $d(robot, O_i) > \varepsilon$
- **Starting point:** Fu, Kishida, and Selinger. "Linear dependent type theory for quantum programming languages." Proceedings of the 35th Annual ACM/IEEE Symposium on Logic in Computer Science. 2020.

Navigation example types

$$
\begin{aligned}
go &: (g : X, n : \mathbb{N}) \to Free \otimes (s : See(n)) \multimap (At(g) \otimes See(n)) \oplus Interrupt(s) \\
Interrupt &: See(n) \multimap Free \otimes (NewObs(See(n+1)) \oplus LoseObs(See(n-1)) \oplus TimeStep)) \\
detect &: See(n) \multimap See(n-1) \oplus See(n) \oplus See(n+1) \\
nearestObs &: See(n) \to List(X) \\
projGoal &: ConvHull(n) \to X \to X \\
voronoi &: See(n) \to ConvHull \\
ConvHull &= List(X) \\
Safe &= (s : See(n)) \to d(x, nearestObs(s)) > R \\
controller &: (g : X) \to (c : Free \otimes See(n) \multimap At(g) \otimes (m : \mathbb{N}, See(m)), Safe(c))
\end{aligned}
$$

Semantics of simple types

Type	Template	Presheaf (evaluated at $U \subset B$)
$See(n)$	$(X^n \times \mathbb{R}^n, 0)$	$\lvert\pi_0(f^{-1}([0, M]))\rvert = n$ for all $f \in \pi_{C(S^1, \overline{\mathbb{R}}_{\geq 0})}(U)$
$Free$	$(*, *)$	$\top$
$At(g)$	$(X, \nabla\lVert x - g\rVert^2)$	$\sup_{x \in U} d(x, g) < \epsilon$
$Safe$	$(X, -\sum_i \nabla\lVert x - o_i\rVert^2)$	$\sup_{x \in U, o \in \bigcup_i O_i} d(x, o) > r$

Integration with LTL-based controller synthesis

1. What LTL buys you
    a. **Automatic synthesis**
        i. Kress-Gazit, Fainekos, and Pappas. "Temporal-logic-based reactive mission and motion planning." IEEE transactions on robotics, 2009
    b. Provable safety/finite-time task completion for **particular control systems** using (control) Lyapunov/barrier functions
2. What dependent LL buys you
    a. **Correct-by-construction composition** of subcontrollers
    b. Physical grounding
        i. Extend safe/unsafe sets with **dynamic interfaces** between behaviors
3. Complementary -- embed LTL specs into dependent linear types
    a. Example: “Eventually(Always(g))” becomes “($A \multimap B$) and g(supp(B)) ”
    b. Use synthesized controllers in correct-by-construction composite controllers

Operational semantics

1. No simple notion of abstract machine/lambda calculus for operational semantics
2. Can we define a “gradual” version of operational semantics based on template-anchor hierarchies?
   a. Examples
      i. Anchor At(g) point attractor template in a differential drive robot
      ii. Anchor See(n) template inside navigation + sensing product corresponds to stabilizing sensor readings
   b. Related work: New and Licata. “Call-by-name gradual type theory.” Logical Methods in Computer Science, 2020.

Thanks for listening!