Complete Heterogeneous Self-Reconfiguration: Deadlock Avoidance Using Hole-Free Assemblies

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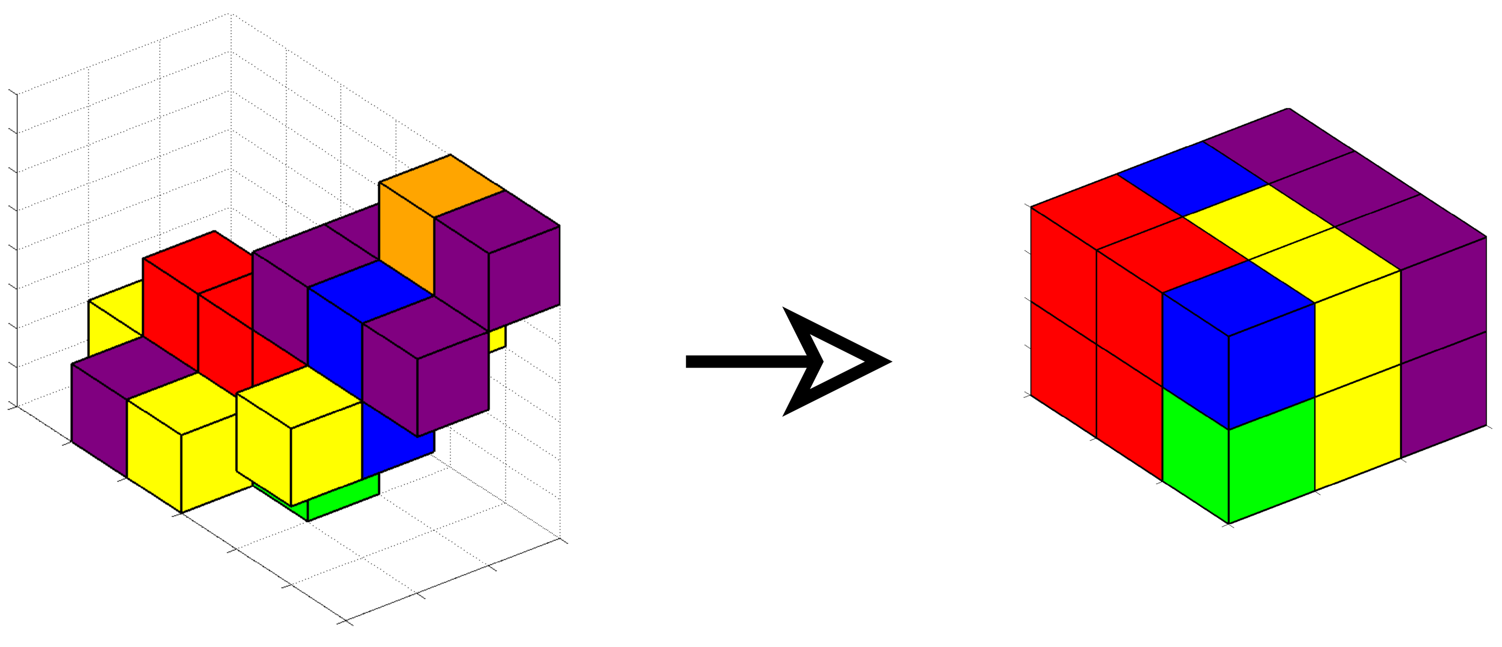
Introduction

What is heterogeneous self-reconfiguration?

- A self-reconfigurable robot is comprised of individual modules.
- Modules have different properties (e.g. shape, size) and/or different capabilities.
- Goal: Reconfigure an initial configuration $\mathcal{C}_I$ into a target configuration $\mathcal{C}_T$.

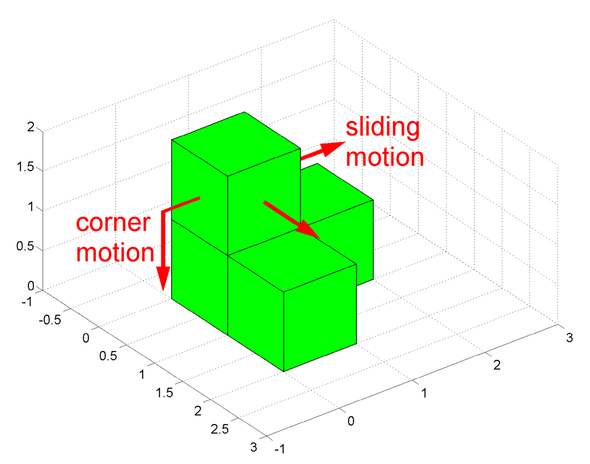


Motivation for heterogeneous self-reconfiguration.

- These systems can adapt to tasks by changing their morphology.
- Such systems can be easily extended and repaired by adding new modules.

System Representation

- Modules are represented by unit cubes.
  - ▷ Dimension $\delta = 1$
  - ▷ Origin $x_i \in \mathbb{Z}^3$
  - ▷ Properties $p_i \in P$
- Cubes are embedded in a discrete three-dimensional unit lattice.



Assumptions and Constraints

Assumptions:

- The initial overlap of $\mathcal{C}_\mathcal{I}$ and $\mathcal{C}_\mathcal{T}$ is exactly one cube.
- The initial and final configurations are hole and enclosure-free.

Constraints:

- Connectivity constraint: The configuration has to remain connected at all times.
- Permanence constraint: Once a cube reaches its target it remains fixed to that position.

Planning Approach

Self-reconfiguration requires to move every cube $c_i \in \mathcal{C}_I \setminus \mathcal{C}_T$ to a matching position in the target configuration $\mathcal{C}_T$.

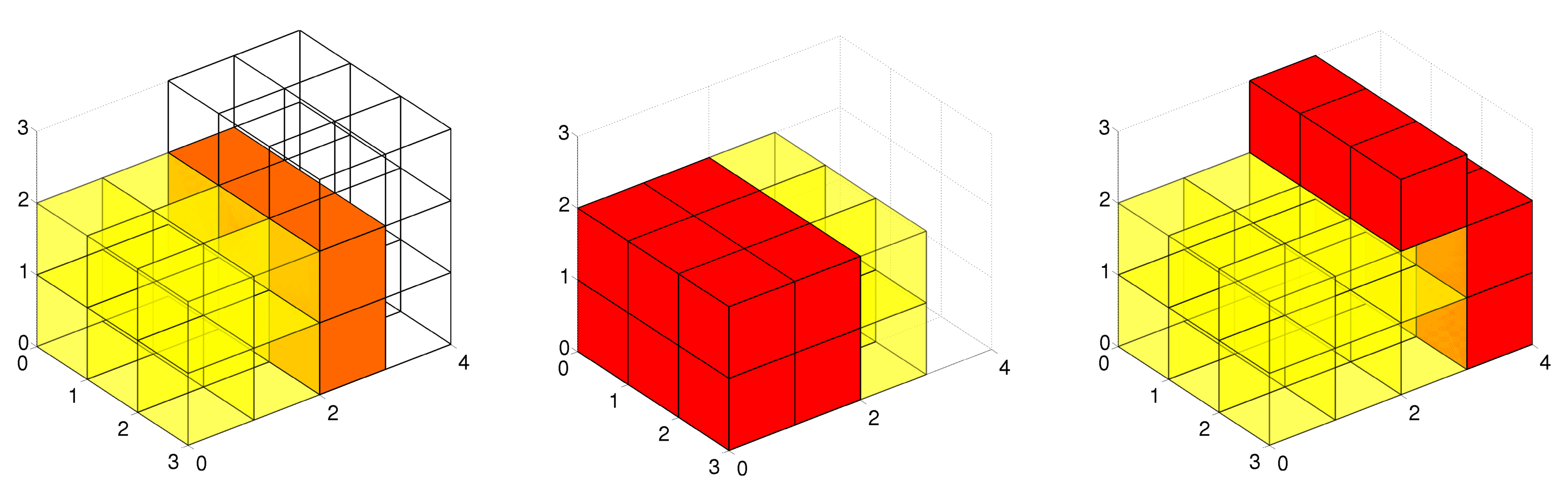
At each iteration, do the following:

- Determine the movable set $\mathcal{M}$, i.e. which cubes can currently be moved.
- Determine the reachable set $\mathcal{R}$, i.e. which target positions can currently be reached.
- Assign a movable cube $c_i \in \mathcal{M}$ to a target position $r_i \in \mathcal{R}$ or execute assignment resolution.
- Determine the planning space $\mathcal{N}$ through which a path can be planned.
- Plan a path p_i from c_i to r_i through $\mathcal{N}$ and execute p_i.

Overlapping set $O = \mathcal{C} \cap \mathcal{C}_T$

Movable set $M = \mathcal{C} \setminus (A \cup I \cup \mathcal{C}_T)\}$

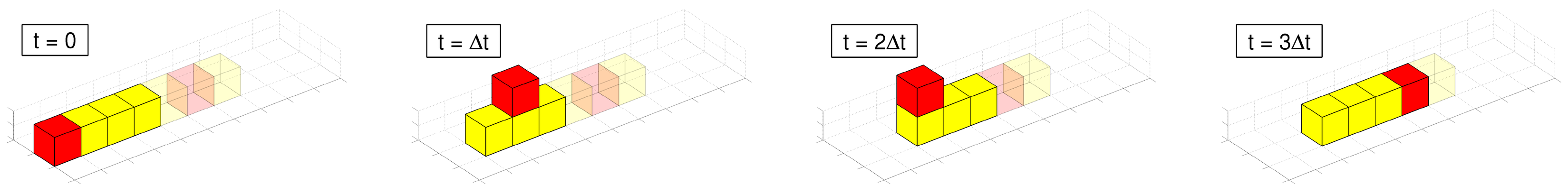
Reachable set $R = \mathcal{N} \cap \mathcal{C}_T$



Assignment Resolution / Deadlock Avoidance

Planning a path requires a valid assignment of a cube $c_i \in \mathcal{M}$ to a position $r_i \in \mathcal{R}$ with matching properties. The absence of valid assignment creates deadlocks that we resolve using assignment resolution.

- A **valid assignment** is a pair $a_i = \{c_i, r_i\}$ with $c_i \in M$ and $r_i \in R \setminus H_t$ such that $p_k(c_i) = p_k(r_i)$, $\forall p_k \in P$ (with P being the set of properties and H_t the set of positions that would create holes).
- **Assignment resolution** moves a movable cube to a random position $m_i = \mathrm{rand}(\mathcal{N}(\mathcal{C}) \setminus R)$ if no cube $c_i \in M$ matches all properties p_k of any position $r_i \in R$,



- **Fact:** Assignment resolution will enable the computation of a valid assignment with probability 1.
- **Fact:** Using assignment resolution, the reconfiguration algorithm guarantees a successful reconfiguration in the absence of holes.

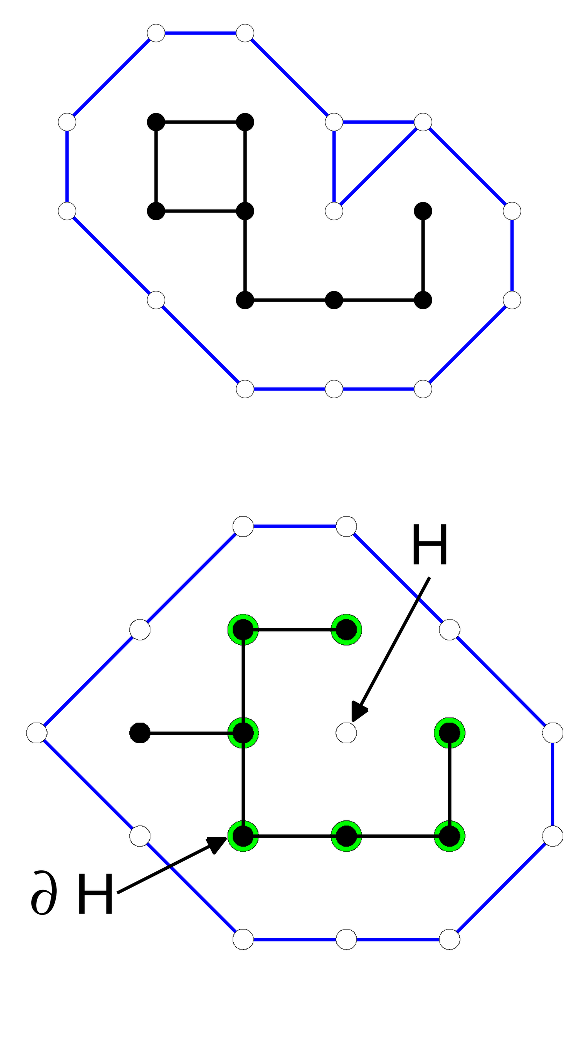
Hole Detection

- A hole H is an unreachable empty target position or a set thereof.
- The boundary of a hole ∂H separates H from the rest of the planning space $N(\mathcal{C})$.
- A hole exists if $N(\mathcal{C})$ contains two or more connected components.
- Hole detection is based on Graph Laplacian of $N(\mathcal{C})$, by which the number of connected components is computed.
- **Fact:** The hole detection algorithm detects a hole iff there exists a hole.

Algorithm 1 Hole Detection

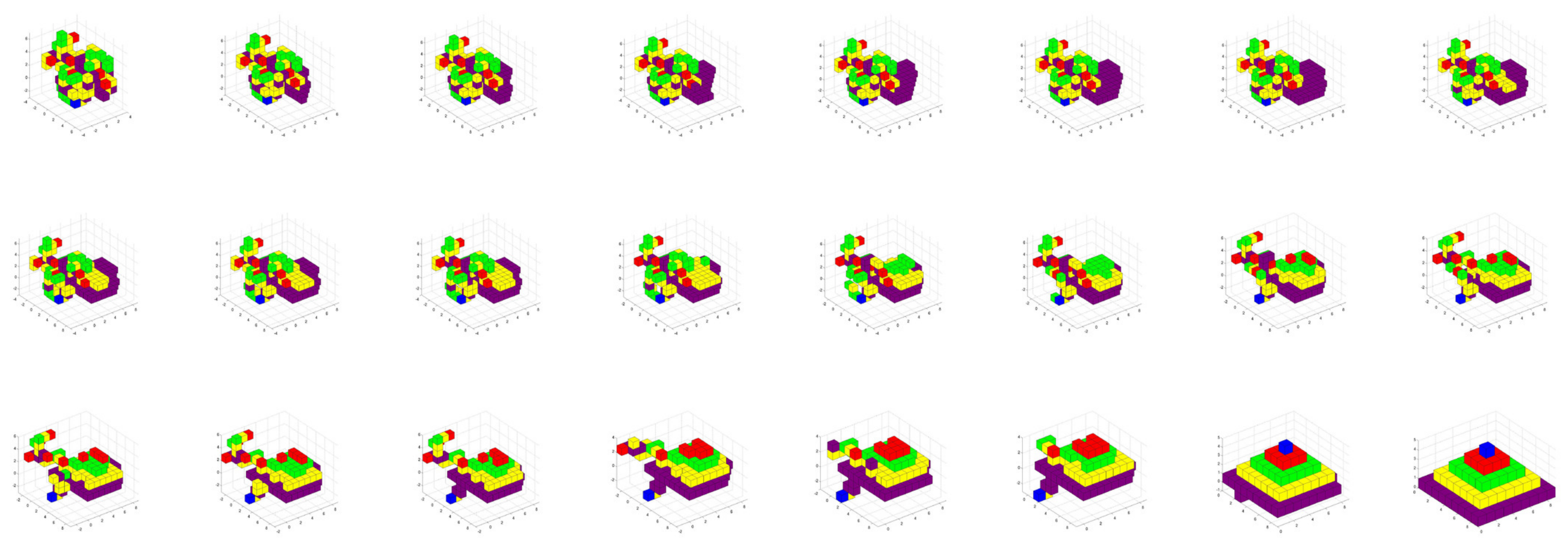
Require: input $a = \{c_i, r_i\}$, $\mathcal{C}$

Compute $\mathcal{N}(\mathcal{C})$
Compute G_C of $\mathcal{N}(\mathcal{C})$
Compute L of G_C
if $|\lambda_i = 0| > 1$ **then**
  Return true
else
  Remove r_i from $\mathcal{N}(\mathcal{C})$
  Update c_i's origin to r_i (in $\mathcal{C}$)
  Recompute $\mathcal{N}(\mathcal{C})$, G_C, and L
  if $|\lambda_i = 0| > 1$ **then**
    Return true
  else
    Return false
  end if
end if



Simulation Results

Size	Steps	Detected Holes	# of Resolutions
10	33	0	3
20	69	0	1
30	107	0	0
40	150	0	0
50	233	0	1



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