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PRACSYS LAB

Efficient and High-quality Prehensile Rearrangement in Cluttered and Confined Spaces

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DATA-INSPIRE TRIPODS Institute

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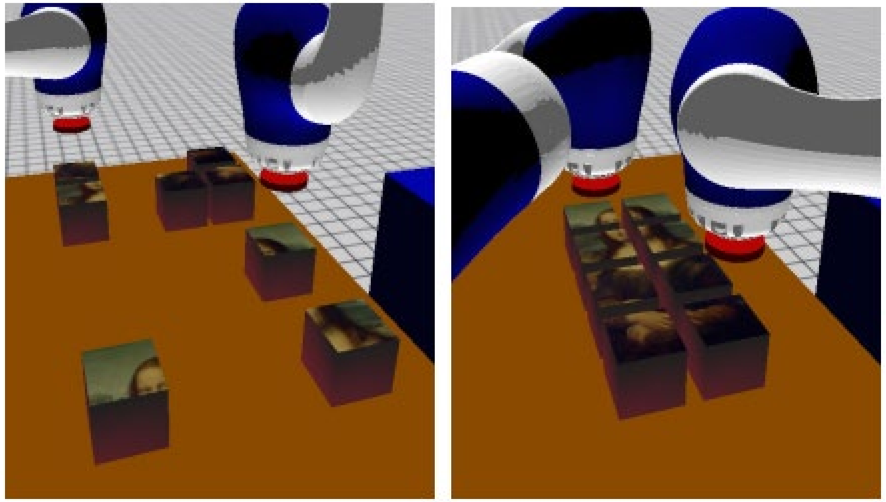
Rearrangement in cluttered and confined spaces

vs.

Rearrangement in tabletop setup



1. Clutter: The robot cannot directly access all objects – the swept volume of the robot may cause robot-object collisions

2. Limited/Confined manipulation space: Once an object is grasped, it cannot be lifted high enough – cannot waive object-object collisions

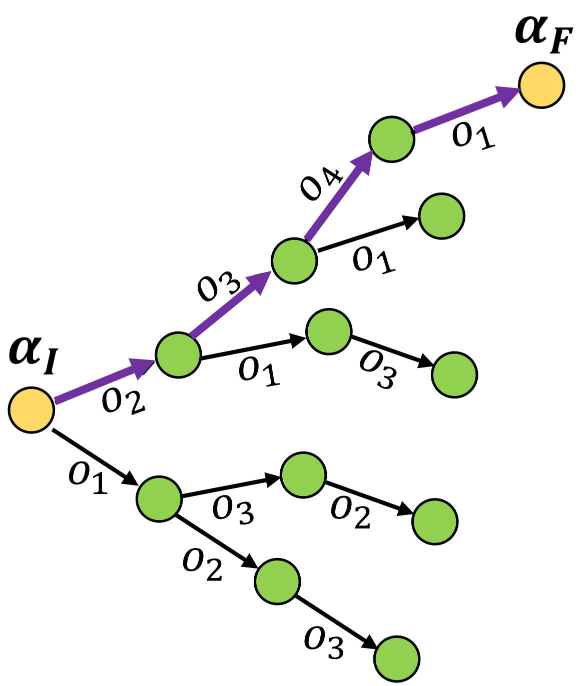
3. Must take both robot-object constraints and object-object constraints into account.

1. Allow the robot to reach the majority of objects at any point in time by using top-down grasps – simplify robot-object interactions

2. Once an object is grasped, it can be lifted sufficiently high relative to other objects – assume no object-object collisions

3. The only hard constraints arise from the potential between the start and goal poses of objects

Search for an ordering with which object are rearranged to successfully fulfill the task



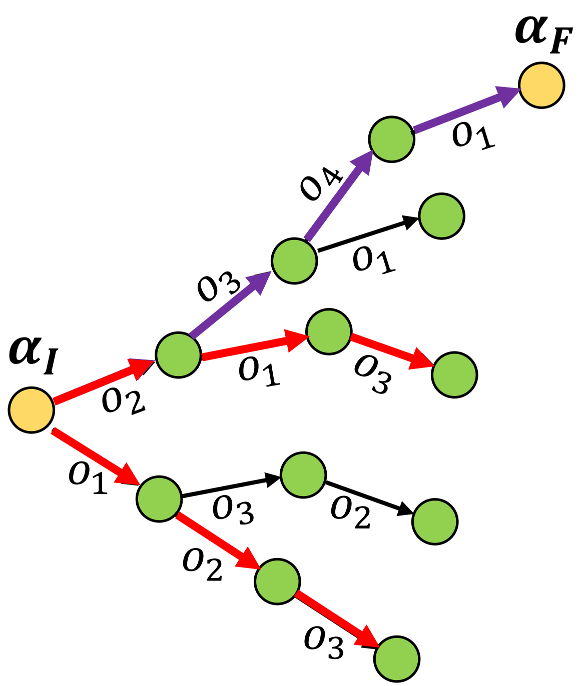
Monotone: Objects need to be moved at most once to solve the problem.
Non-monotone: At least one object needs to be moved to a buffer before moved to its goal.

Complexity: $O(n!)$: Does not scale well with the number of objects

M. Stilman, J.-U. Schamburek, J. Kuffner, and T. Asfour, "Manipulation planning among movable obstacles," in Proceedings 2007 IEEE international conference on robotics and automation. IEEE, 2007,pp. 3327–3332.

Search for an ordering with which object are rearranged to successfully fulfill the task

Kai Gao



Monotone: Objects need to be moved at most once to solve the problem.
Non-monotone: At least one object needs to be moved to a buffer before moved to its goal.

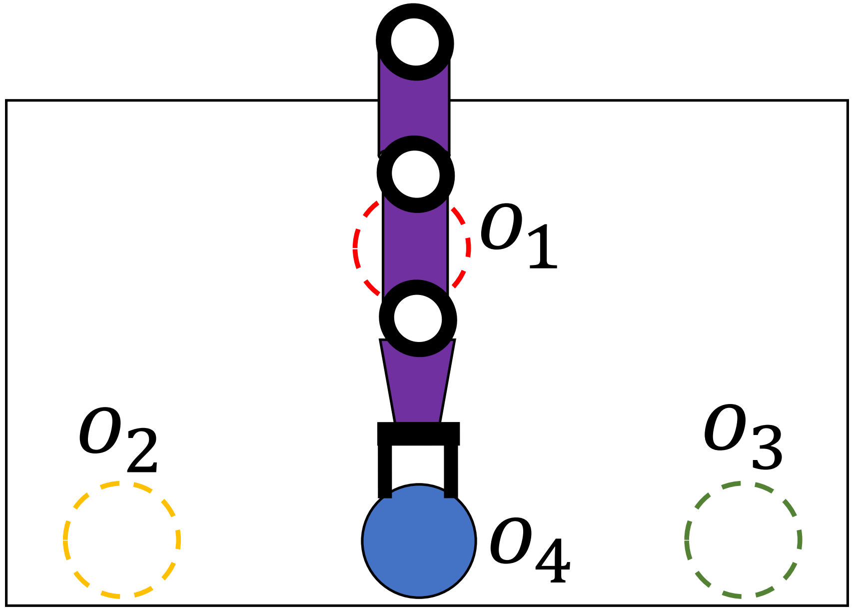
Complexity: $O(n!)$: Does not scale well with the number of objects

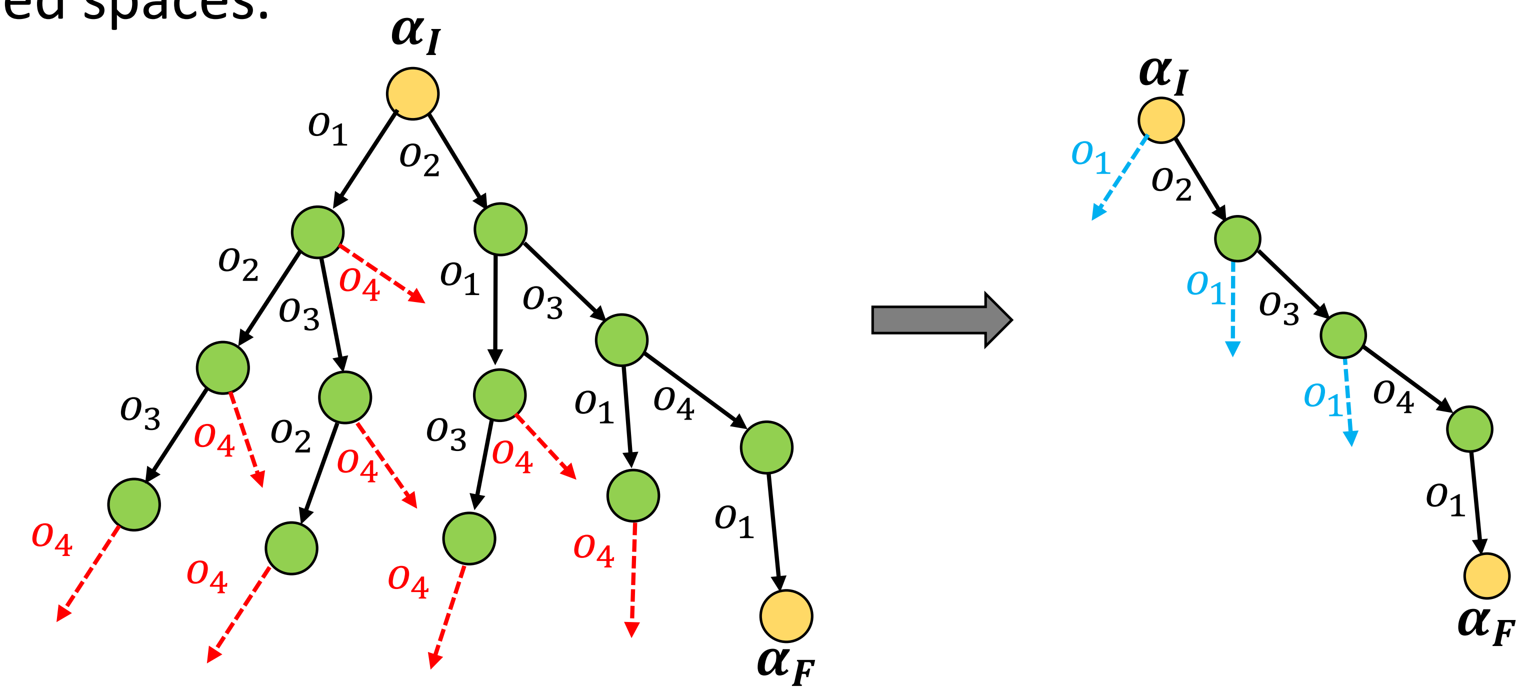
Observation: Instead of searching the space of all object permutations $O(n!)$ to solve monotone instances, it is sufficient to search the space of object arrangements $O(2^n)$.

R. Wang*, K. Gao*, D. Nakhimovich*, J. Yu, and K. E. Bekris, "Uniform object rearrangement: From complete monotone primitives to efficient non-monotone informed search," in IEEE International Conference on Robotics and Automation, 2021

Observation: Even in the reduced arrangement space, there is a lot of redundancy.

Some branches of the search tree will not lead to a solution, as they violate constraints enforced in cluttered and confined spaces.



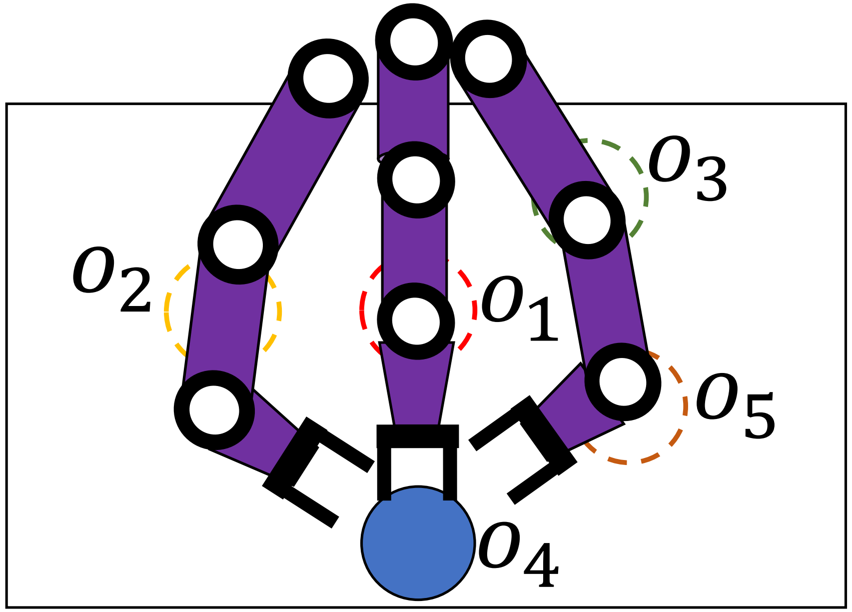


Don’t move o_4 when o_1 is at the goal!!

Don’t move o_1 when o_4 is at the start…

$$\widetilde{\mathcal{A}}[\boldsymbol{o_1}] = \{\boldsymbol{\alpha} \mid \boldsymbol{\alpha}[\boldsymbol{o_4}] = \boldsymbol{\alpha_C}[\boldsymbol{o_4}]\}$$

Another example



Denote $\mathcal{C}_4^j$ as the colliding object set, where the goals of these objects hinder the grasping of o_4 for the j-th configuration.

$$\mathcal{C}_4^1 = \{o_2\}, \mathcal{C}_4^2 = \{o_1\}, \mathcal{C}_4^3 = \{o_3, o_5\}$$

$$\mathcal{C}_4^1 \times \mathcal{C}_4^2 \times \mathcal{C}_4^3$$

$$c^1 = \{o_1, o_2, o_3\}$$
$$c^2 = \{o_1, o_2, o_5\}$$

$$c^1 = \{o_1, o_2, o_3\}$$

Don’t move o_4 when o_2, o_1, o_3 are all at their goals!!!

Don’t move o_1 when o_4 is at start while o_2, o_3 are both at their goals….

$$\widetilde{\boldsymbol{\mathcal{A}}}[\boldsymbol{o_1}] = \{\boldsymbol{\alpha} \mid \boldsymbol{\alpha}[\boldsymbol{o_4}] = \boldsymbol{\alpha_C}[\boldsymbol{o_4}], \boldsymbol{\alpha}[\boldsymbol{o_2}] = \boldsymbol{\alpha_F}[\boldsymbol{o_2}], \boldsymbol{\alpha}[\boldsymbol{o_3}] = \boldsymbol{\alpha_F}[\boldsymbol{o_3}]\}$$

Constraint Informed Rearrangement Solver (CIRS)

Algorithm 1: CIRS(α_C, α_F, $\mathcal{O}$, K)

$\mathcal{A}_{invalid}$ = DetectInvalidity($\alpha_C, \alpha_F, \mathcal{O}, K$)
return CIDFS$_{DP}$($\emptyset, \alpha_C, \alpha_F, \mathcal{A}_{invalid}$)

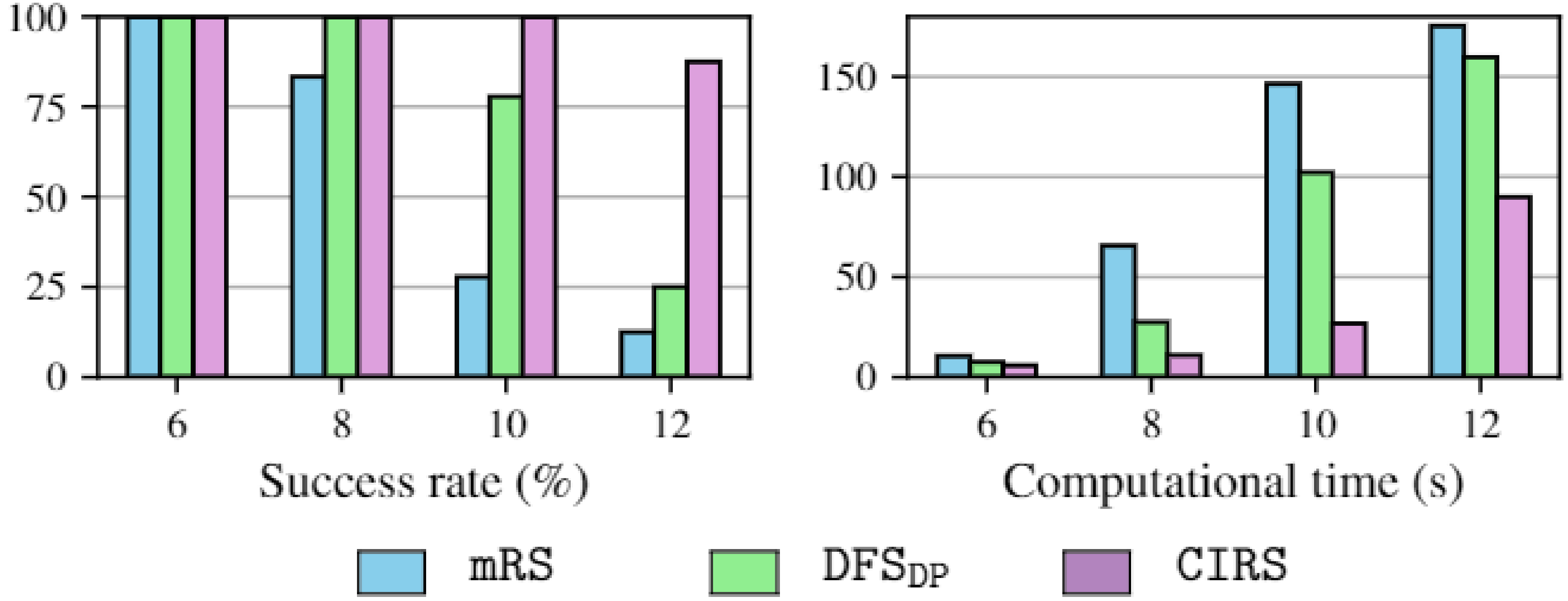
Algorithm 2: DetectInvalidity(α_C, α_F, $\mathcal{O}$, K)

for $o_i \in \mathcal{O}$ **do**
  $\mathcal{A}_{invalid}[o_i] = \emptyset$
for $o_i \in \mathcal{O}$ **do**
  $[q^1, \cdots, q^K], [\mathcal{C}_i^1, \cdots, \mathcal{C}_i^K] =$ GenerateArmConfigurations(α_C, α_F, K)
  for $c^j \in \{\mathcal{C}_i^1 \times \cdots \times \mathcal{C}_i^K\}$ **do**
    $\widetilde{\mathcal{A}} =$ ElicitArrangements(c^j)
    $\mathcal{A}_{invalid}$.ADD($\widetilde{\mathcal{A}}$)
return $\mathcal{A}_{invalid}$

Algorithm 3: CIDFS$_{DP}$(T, α_C, α_F, $\mathcal{A}_{invalid}$)

for $o \in \mathcal{O} \backslash \mathcal{O}(\alpha_C)$ **do**
  if $\alpha_C \in \mathcal{A}_{invalid}[o]$ **then** continue
  $\alpha_{new}[\mathcal{O} \backslash \{o\}] = \alpha_C[\mathcal{O} \backslash \{o\}]$
  $\alpha_{new}[o] = \alpha_F[o]$
  if $\alpha_{new} \notin T$ **then**
    $\pi \leftarrow$ MotionPlanning(α_C, α_{new}, o)
    if $\pi \neq \emptyset$ **then**
      $T[\alpha_{new}].parent \leftarrow \alpha_C$
      if $\alpha_{new} \neq \alpha_F$ **then**
        T = CIDFS$_{DP}$(T, α_{new}, α_F, $\mathcal{A}_{invalid}$)
      if $\alpha_F \in T$ **then return** T
return T

Experimental results



Other contributions in the current line of work

1. Propose a non-monotone global framework for solving non-monotone problems with high-quality solutions, i.e., fewer actions in total to fulfill a task.

2. Propose a pre-processing tool (labeled roadmap) which significantly speeds up online motion planning query.

Future Work

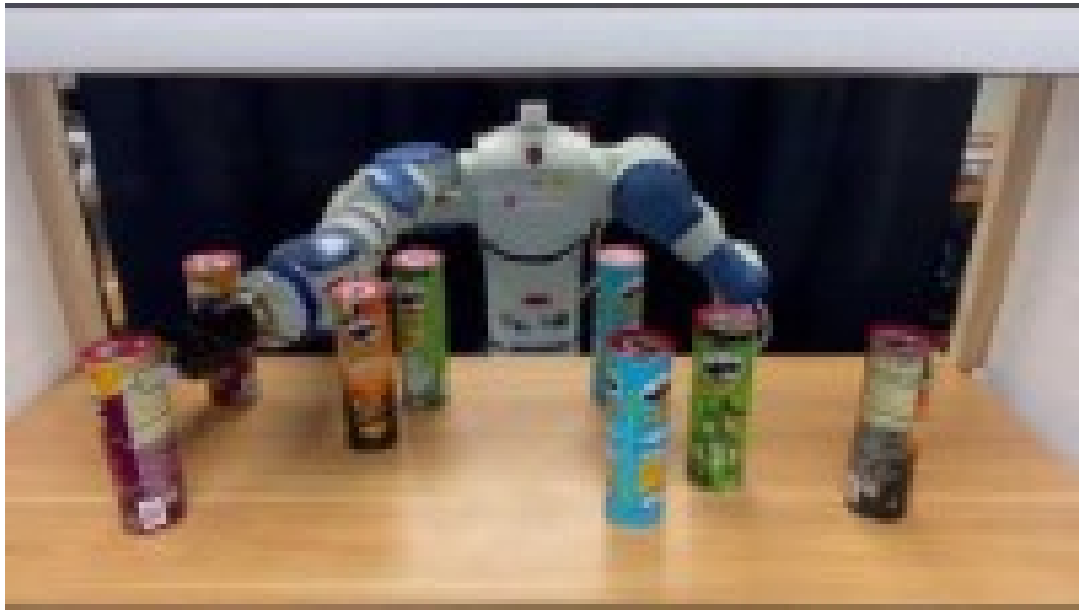
1. Generalize all the possible constraints to save more computational time.

2. Learn failure cases during the search.

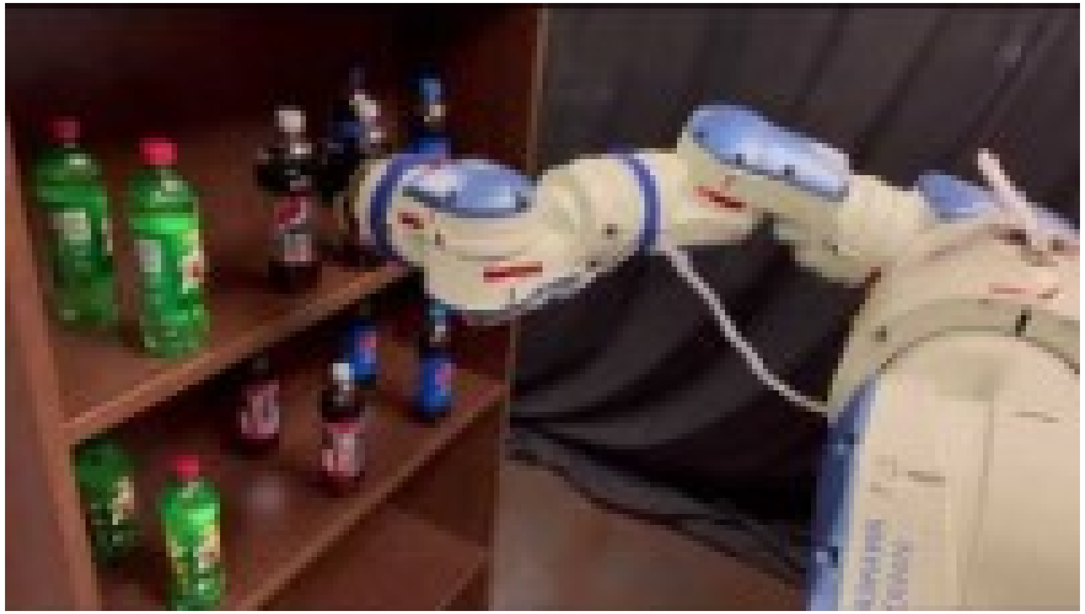
3. See if we can come up with a better default object ordering with which the search uses as a heuristic.

4. Better reasoning about object and buffer selection in tackling non-monotone problems.

Demonstration



Yinglong Miao



Reference

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Thanks for Listening!

Acknowledgments
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