UC San Diego

Geometric In-Hand Regrasp Planning- Alternating Optimization of Finger Gaits and In-Grasp Manipulation

Presenter: [Shaowei Liu]

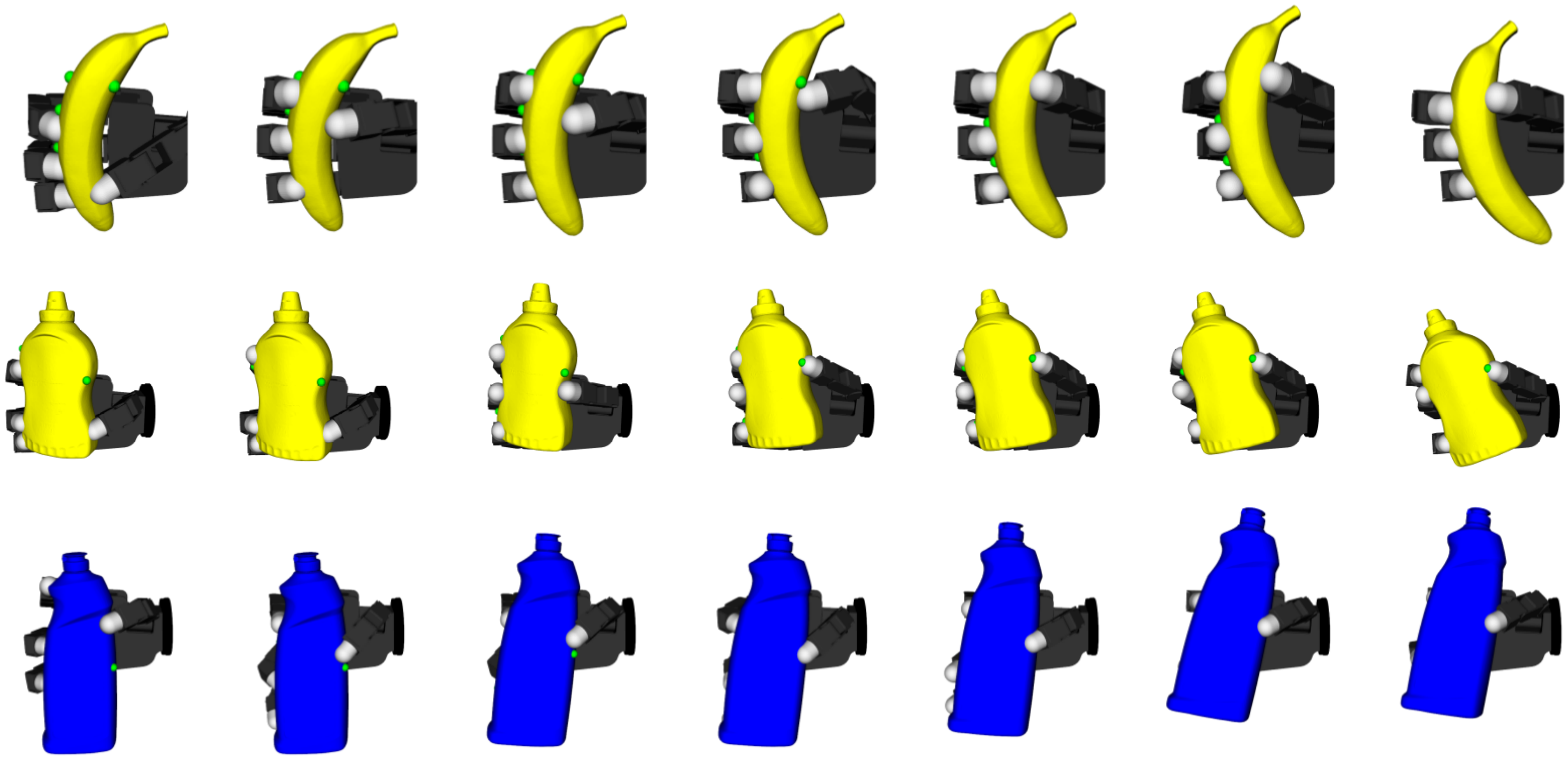
[2020.5.12]

Outline

- Introduction
- Related work
- Method
- Experiments
- Conclusion

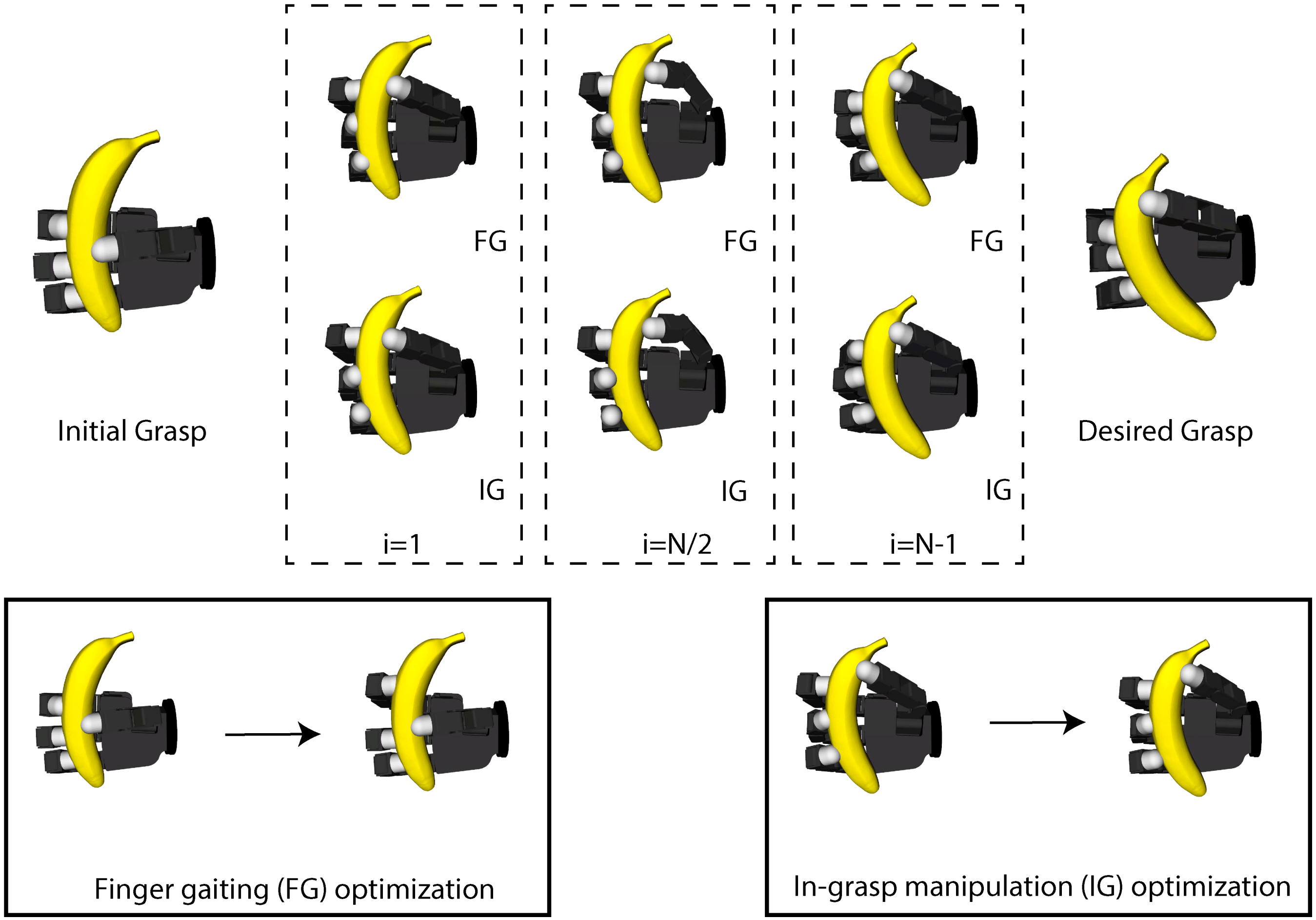
Background

- In-hand regrasping



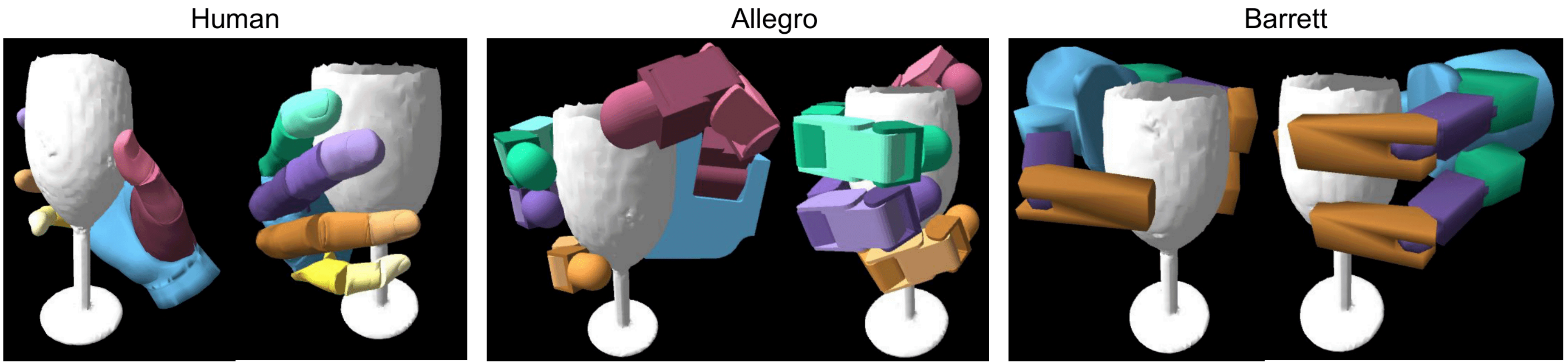
Overview

- Moving from an initial grasp on an object to a desired grasp, while maintaining contact locations



Introduction

- Allegro Hand

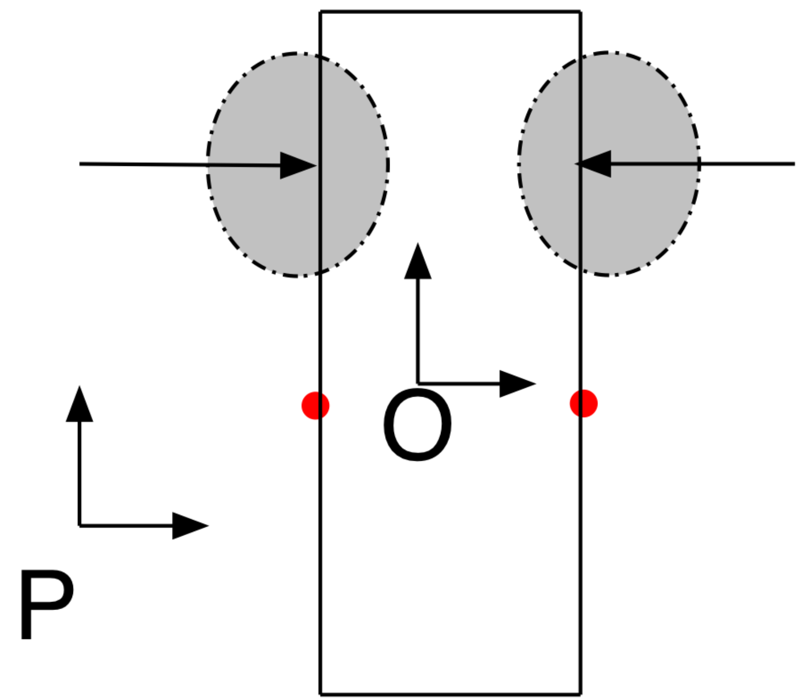


Terminology

- Contact point in R^3
- Joint configuration angle representation Θ
- Forward kinematics (FK), mapping from joint angles to poses

Terminology

- Finger reachable workspace (triangle mesh model by sampling the enclosed volume)



Terminology

- Object Mesh

Open Problems

1) Moving to a set of desired grasp contact points from the current grasp
2) Avoiding unwanted collisions between the object and the hand during manipulation
3) Moving to a desired object pose after reaching the desired grasp contact points
4) Ensuring stability of the object during manipulation
5) Choosing the correct sequence of fingers in performing finger gaiting
6) Planning an initial grasp, which can achieve the desired object pose through in-grasp re-planning

Contributions

- An optimization based framework for planning finger gaits on arbitrary object meshes, which directly solves for collision-free joint angle trajectories

Limitations

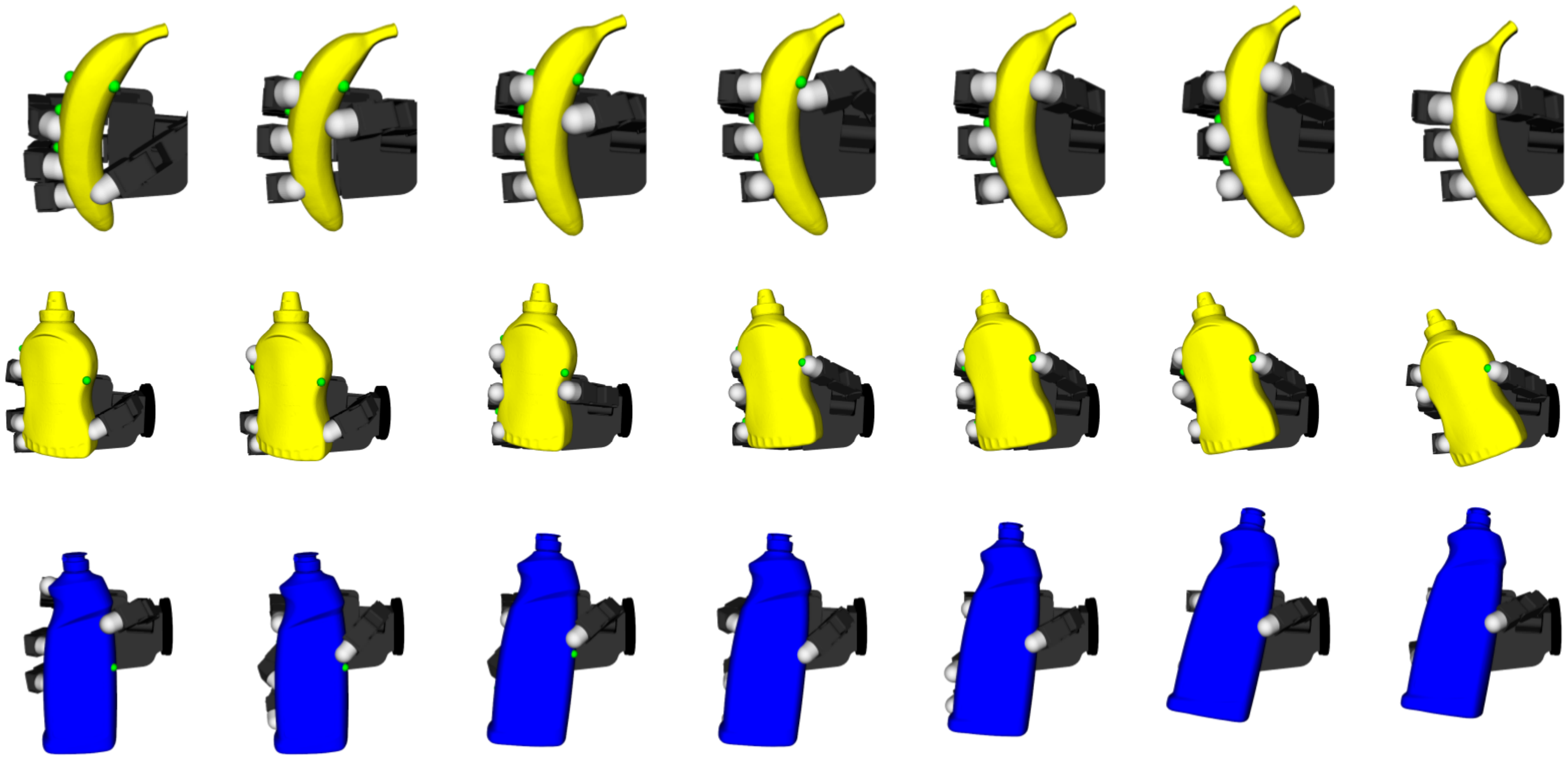
- Not include dynamics, so it would be insufficient for execution on a physical robot
- Contacts are only made at the fingertips

Assumptions

- The object is rigid
- The desired grasp is a stable grasp and the desired object pose is reachable
- Assume that all the fingers can repose their contact on the object. In the case of the thumb, we assume that it can slide to the new contact point
- Generate initial and desired grasps manually

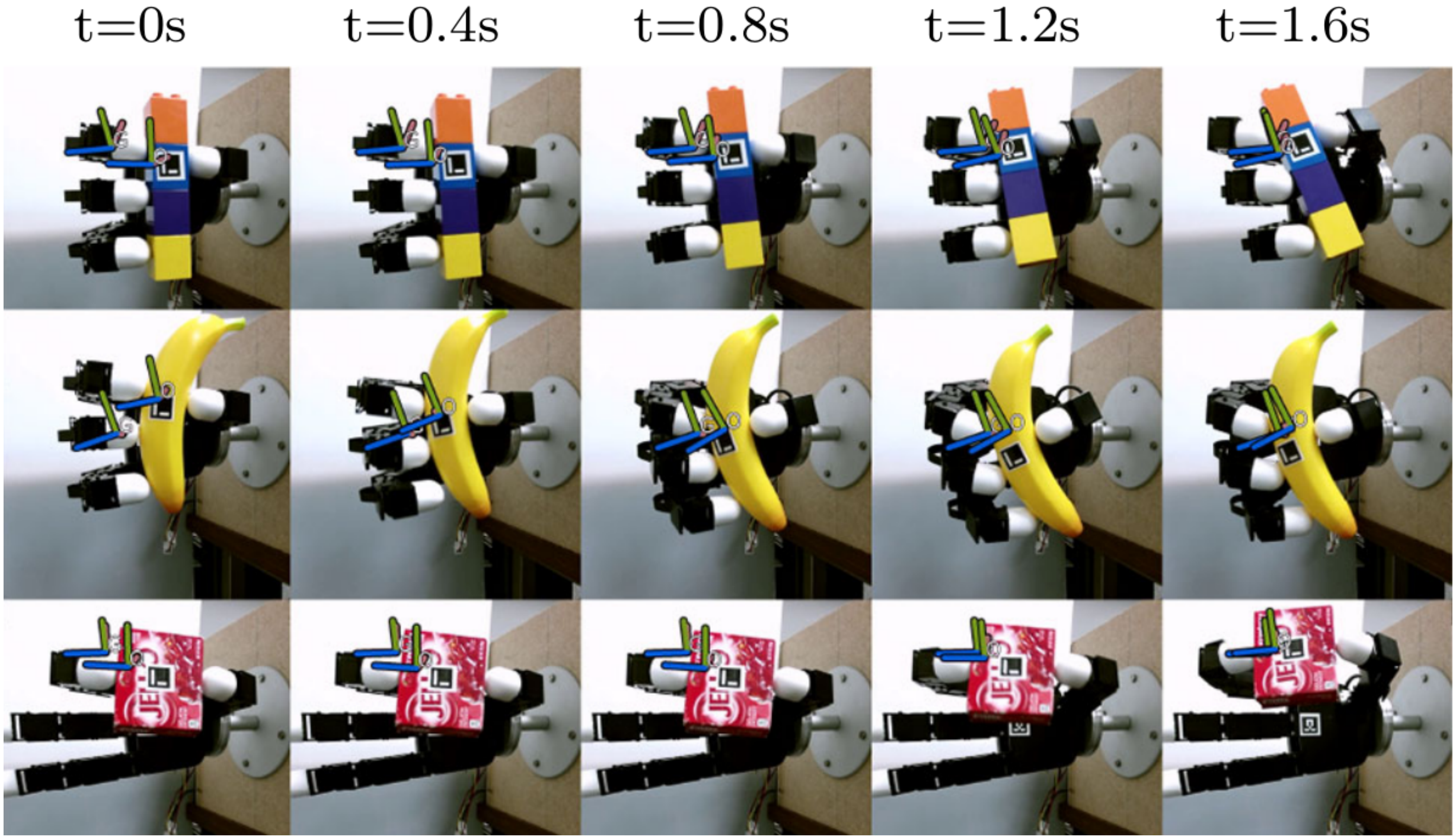
Related Work

- Moving to a set of desired grasp contact points from the current grasp



Related work

- Moving to a desired object pose after reaching the desired grasp contact points



Related Work

- Two categories
- Fingertips always remain in contact
- Fingers break and make new contacts

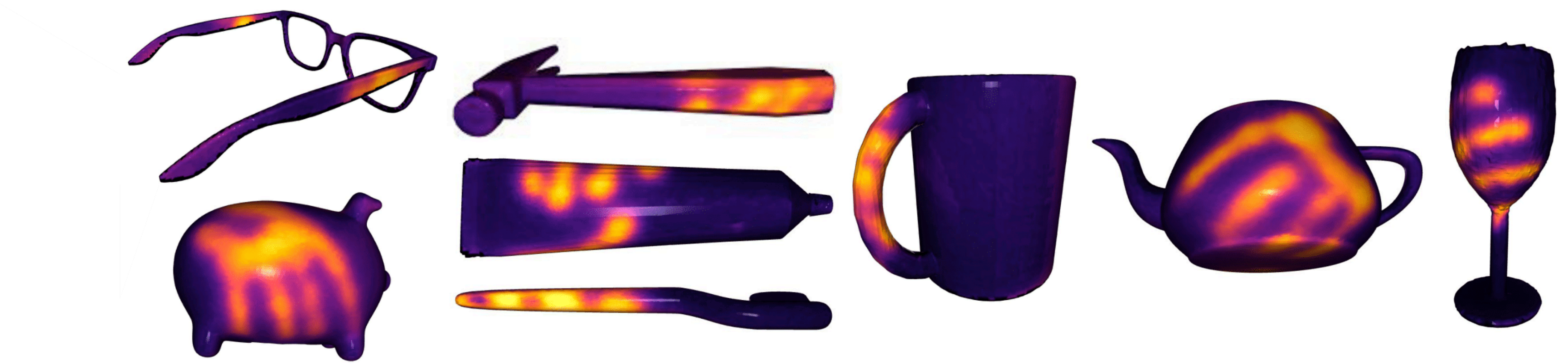
- Solutions
- Enumerate all possible motions and build a search tree
- Find a continuous path in the joint configuration space to a grasp

- Achieve Object pose
- Achieve goal grasp

Related Work

- How to obtain the ground-truth

- Contact Measure



Overview

- Goal: finding a sequence of grasps which moves the moves the fingertip to the the goal finger contact point in N step
- Sequence of grasps $G = [G_0, G_1 \cdots G_N]$
- Each grasp $G_i = [X_i, O_i]$ contains contact points X_i and object pose $O_i \in SE(3)$
- Each contact point $X_i = [f_1, f_2, f_3, f_4]$ where $f_i \in R^3$

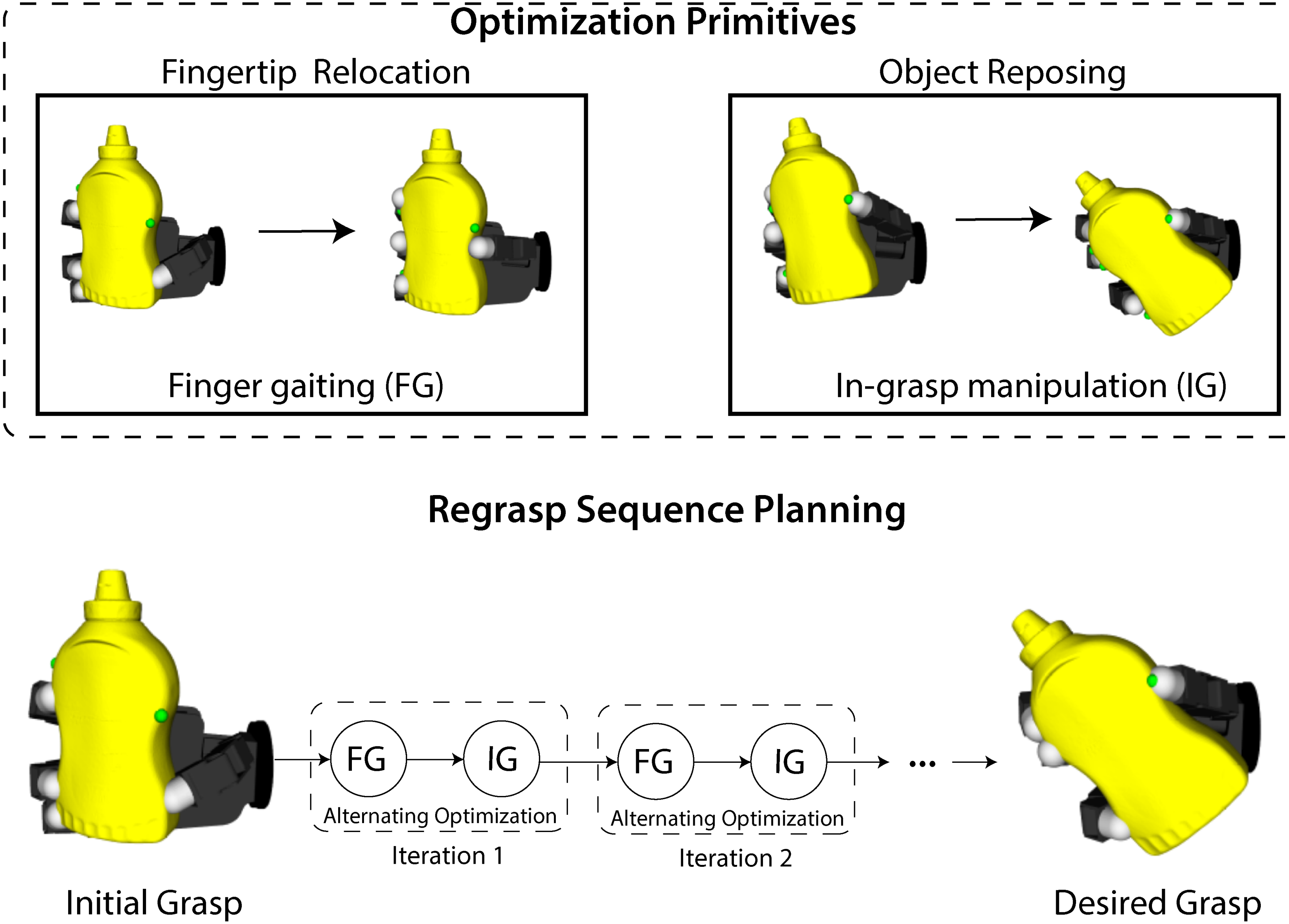
Overview

- At each time step

- Finger-gaiting
- Finding a new location for a fingertip within its reachable workspace.

- In-grasp manipulation
- Moving the object to shift the reachable workspace of the fingertips relative to the object surface.

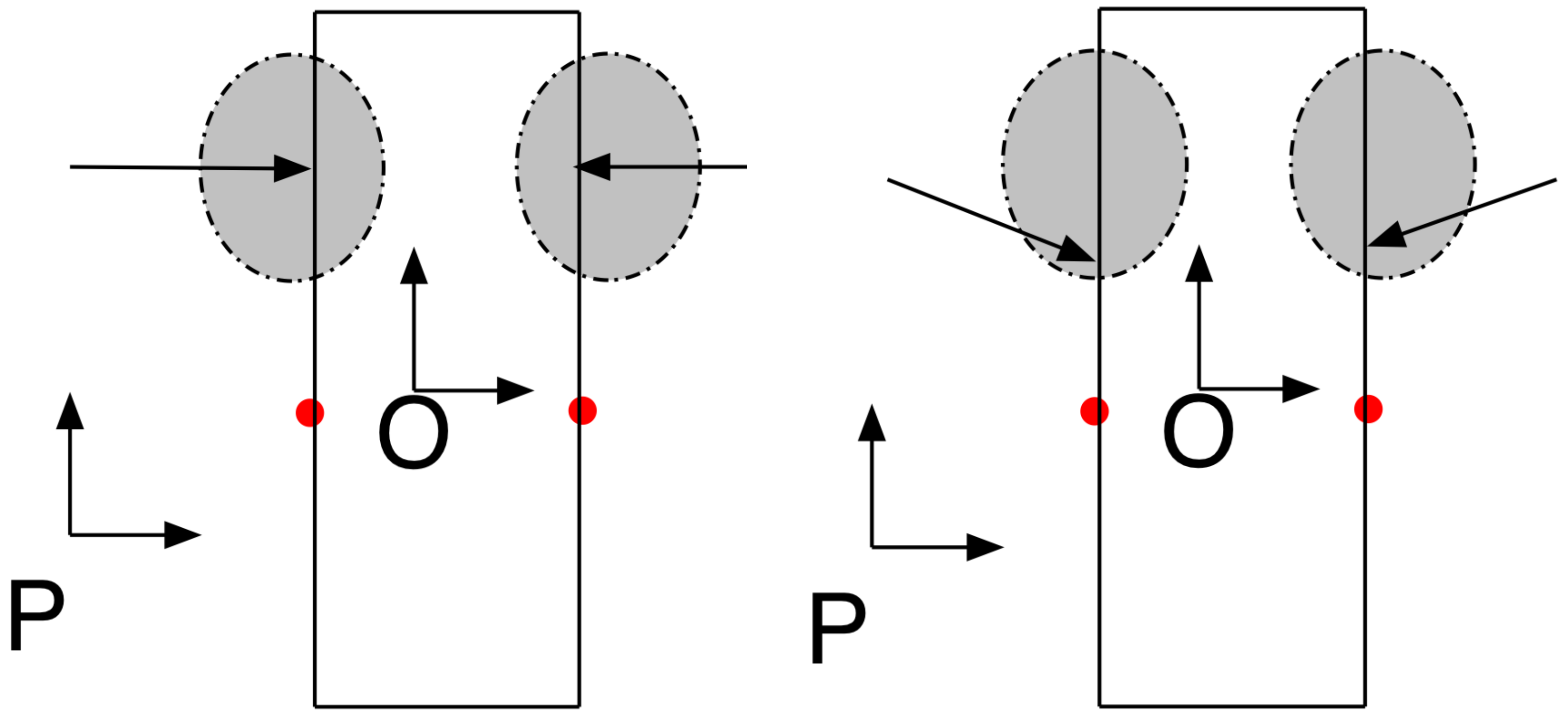
Overview


Optimization Primitives
Fingertip Relocation
Object Reposing
Finger gaiting (FG)
In-grasp manipulation (IG)
Regrasp Sequence Planning
FG
IG
Alternating Optimization
Iteration 1
FG
IG
Alternating Optimization
Iteration 2
...
Initial Grasp
Desired Grasp

OPT1

- Optimization for Finger Gaits (OPT1)
- Moves the contact point f_r of fingertip r towards the goal finger contact point $\mathrm{f}_{r,g}$reachable workspace of finger r
- Geometric optimization problem over the joint angles Θ_r of finger r, while the remaining joints in Θ remain fixed
- A fixed gait pattern {index, middle, ring, thumb} or {thumb,ring,middle,index} according to the desired contact location

OPT1



OPT1

- Optimization for Finger Gaits (OPT1)

$$
\begin{aligned}
\min_{\Theta^r} \quad & D(f_{r,g}, FK_r(\Theta^r)) \\
\text{s.t.} \quad & \\
& \Theta^r_{min} \preceq \Theta^r \preceq \Theta^r_{max} \\
& SD(FK_r(\Theta^r), M) = 0 \\
& C(\Theta^r, M) = 0 \\
& S(FK_r(\Theta^r)) \leq \eta,
\end{aligned}
$$

- Optimize over joint angles Θ_r of finger r

OPT1

- Overall Cost function D

$$D(f_{r,g}, FK_r(\Theta^r)) = ||f_{r,g} - FK_r(\Theta^r)||_2^2$$

- $f_{r,g}$ is the goal contact point for finger r

- FK_r is the forward kinematics for finger r

OPT1

- Joint limit constraints

$$\Theta^r_{min} \preceq \Theta^r \preceq \Theta^r_{max}$$

- Signed distance of fingertip lying on the surface of the object mesh M

$$SD(FK_r(\Theta^r), M) = 0$$

- Collision cost for links of finger r

$$C(\Theta^r, M) = 0$$

- Stability

$$S(FK_r(\Theta^r)) \leq \eta$$

OPT1

- Collision cost C for links L_r of finger r

$$C(\Theta^r, M) = 0$$

- All links on the moving finger maintain at least distance of β from the object mesh M

$$C(\Theta^r, M) = \sum_{l \in L_r} (\beta - \min(\beta, SD(FK_l(\Theta^r), M)))$$

OPT1

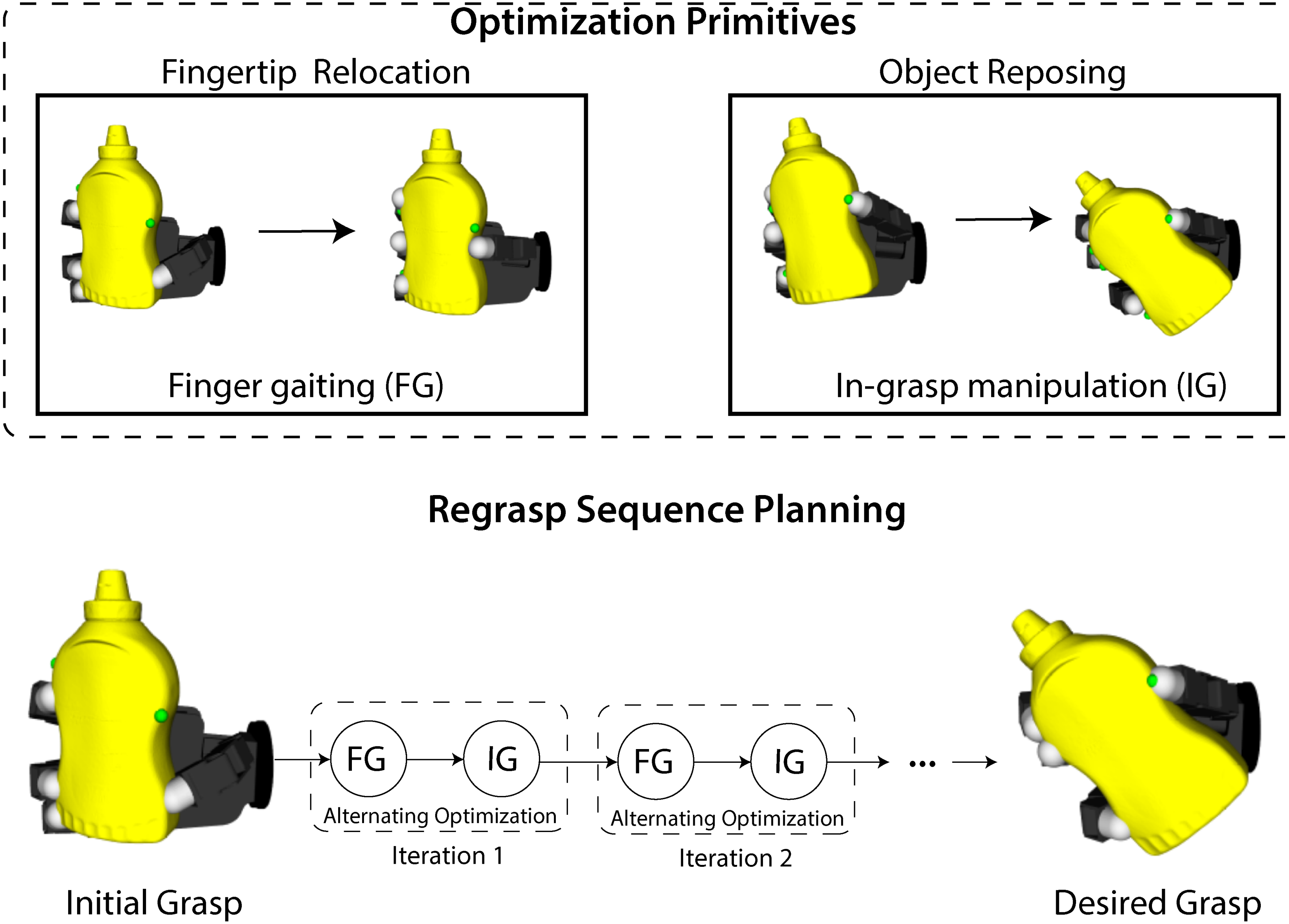
- Stability Cost S
- Limit the finger gait distance to be within a threshold

$$S(FK_r(\Theta^r)) \leq \eta$$

$$S(FK(\Theta^r)) = ||FK_r(\Theta^r_0) - FK_r(\Theta^r)||_2^2$$

- small steps are taken when η is small

Overview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Iteration 2
...
Initial Grasp
Desired Grasp

OPT2

- Optimization for Object Reposing (OPT2)

- Change object pose in order to shift the reachable workspace of the fingertips relative to the object

$$\min_{\Theta} \; E_{des} + k_1 E_{pos}(\Theta) + k_2 E_{or}(\Theta)$$

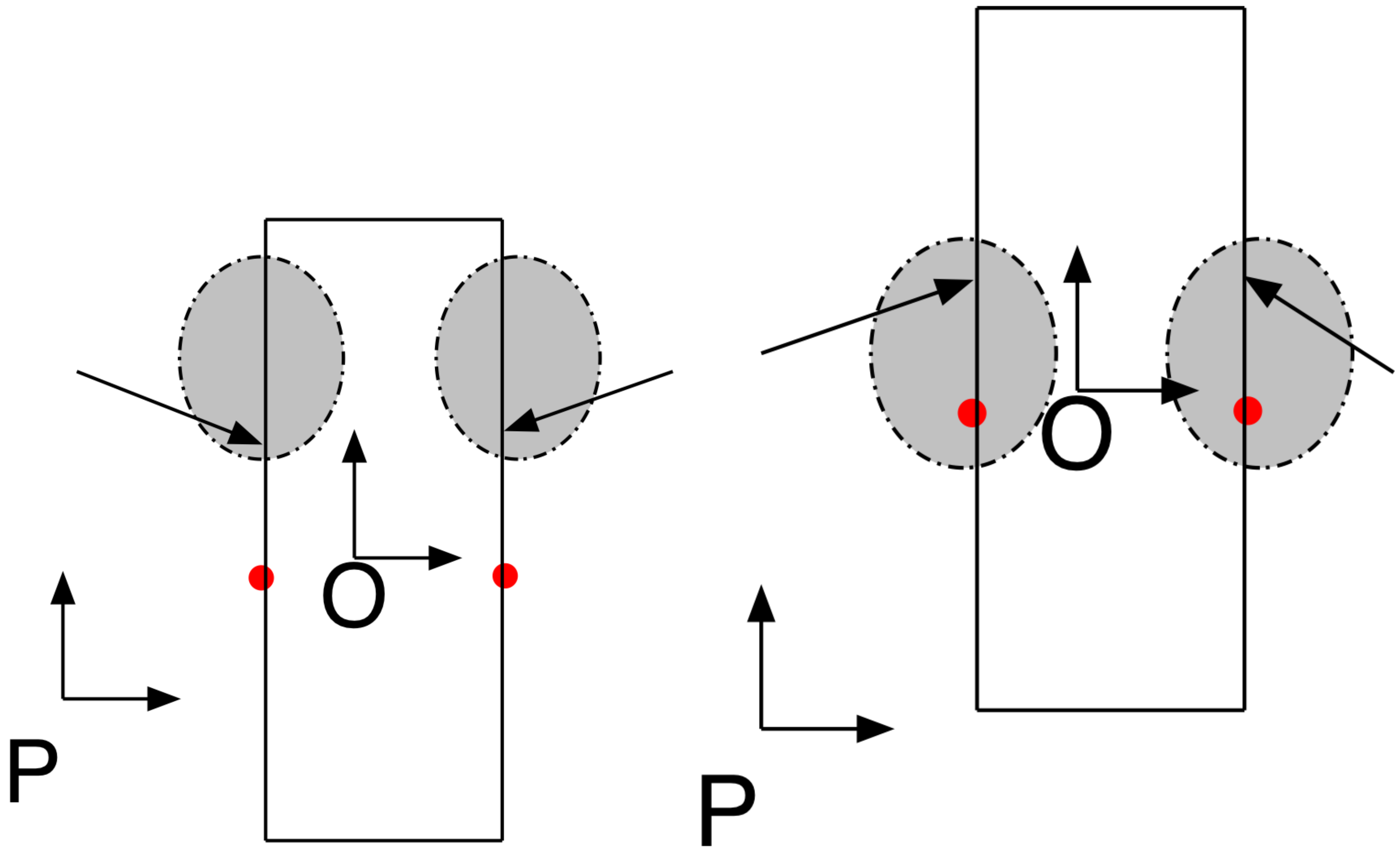
$$\text{s.t.}$$

$$\Theta_{min} \preceq \Theta \preceq \Theta_{max}$$

$$C(\Theta, M) = 0$$

- Optimize over all joint angles Θ

OPT2



OPT2

- Adjust Object pose

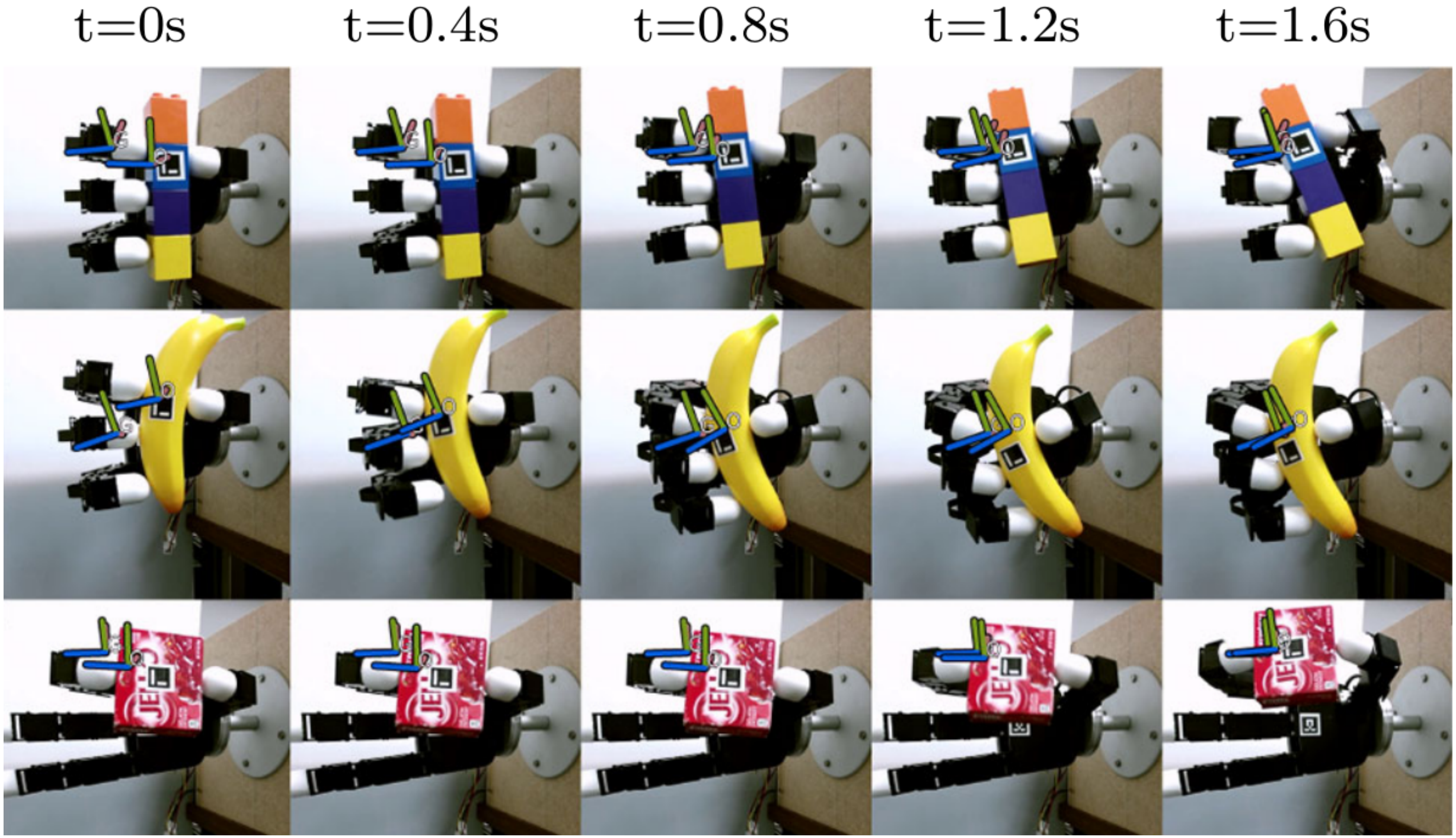
- Solution-1:
- Reduces the distance between the reachable workspace R_r of the finger r and the desired contact points, where m is the number of fingers

$$E_{des} = \sum_{r=0}^{m} \max(0, SD(f_{r,g}, R_r))$$

- Denoted as “SD”

OPT2

- Adjust Object pose



OPT2

- Adjust Object pose

- Solution-2:
- Finding a target object pose $\widehat{O_d}$ and set as target, then solve for the joint angles at the desired object pose
- The target object pose is obtained by ICP algorithm using singular value decomposition

$$E_{des} = E_{obj}(\Theta, \hat{O}_d)$$

- Euclidean distance in world frame
- Denoted as “SVD”

OPT2

- Joint position limits constraint

$$\Theta_{min} \preceq \Theta \preceq \Theta_{max}$$

- Relaxed-rigidity constraint

- $E_{pos}(\Theta)$ encouraging fingertips to keep the same contact locations on the object as in the initial grasp

- $E_{or}(\Theta)$ encourages the other fingers to maintain their relative orientation to the thumb to be the same as that in the initial grasp

- Collision cost C as in OPT1

Pipeline

- Regrasp Planner

Algorithm 1: In-hand Regrasping Planner

Data: M,K_0,X_g,o_g
Result: $\mathbf{K} = [G, \boldsymbol{\Theta}]$

$\mathbf{K} = []$;
$\mathbf{K}$.append(K_0);
err $\leftarrow \max_{r\in[0,m]}(f_{r,0} - f_{r,g})$;
$n = 0$;
while err $> \zeta$ *and* $n < 50$ **do**
    for $i \in P$ **do**
        $K_t \leftarrow$ OPT1($\mathbf{K}$.last, X_g, i);
        $\mathbf{K}$.append(K_t);
    end
    err $\leftarrow \max_{r\in[0,m]}(f_{r,t} - f_{r,g})$;
    if err $> \zeta$ **then**
        $K_t \leftarrow$ OPT2($\mathbf{K}$.last,X_g);
        $\mathbf{K}$.append(K_t);
    end
    $n{+}{+}$;
end
$K_t \leftarrow$ in_grasp($\mathbf{K}$.last, o_g);
$\mathbf{K}$.append(K_t);
return $\mathbf{K}$;

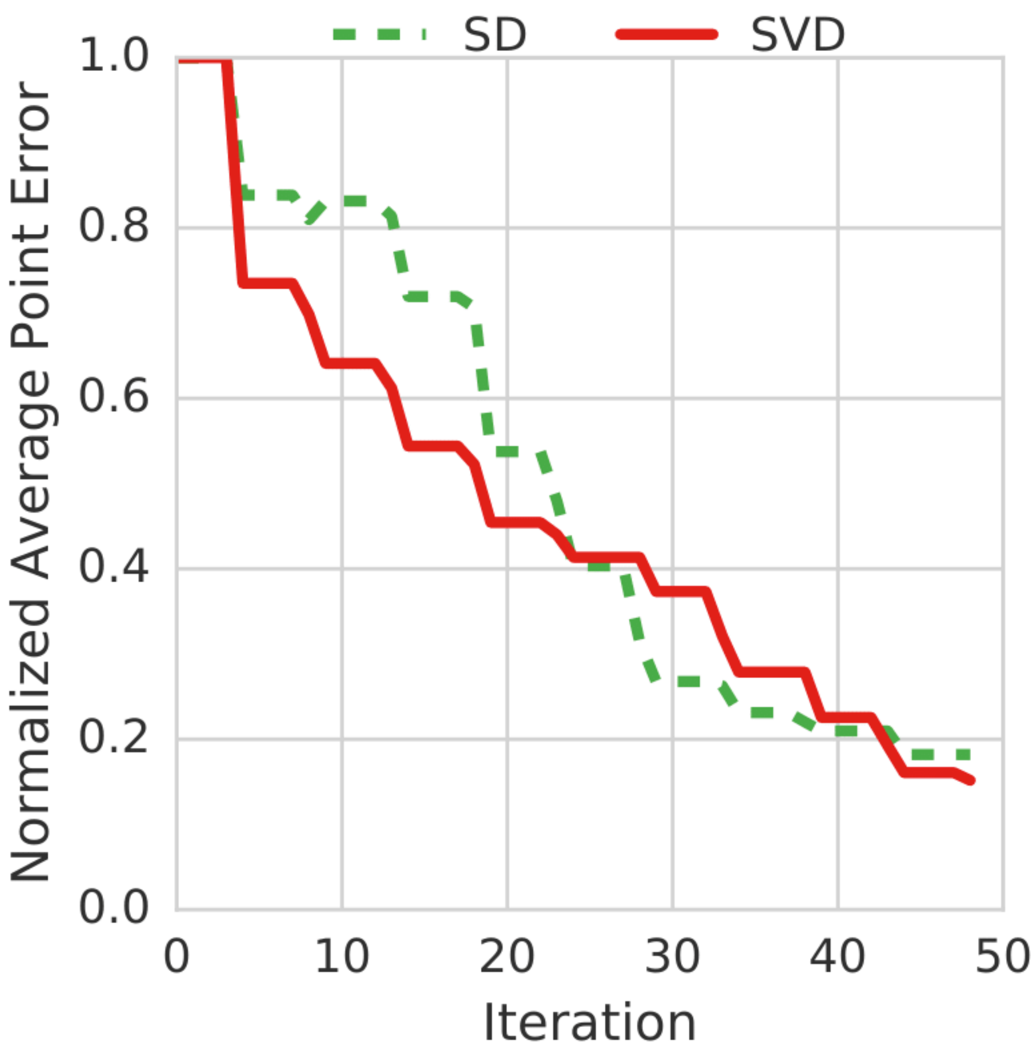
Methods

- Optimization
- sequential quadratic programs (SQP)
- Maximum number of iterations to 50

- Evaluation
- Average Point Error: error between the planned and desired final grasp contact grasp contact points using Euclidean distance over all fingers
- Convergence rate
- Planning Time

Experiments

- Convergence Rate



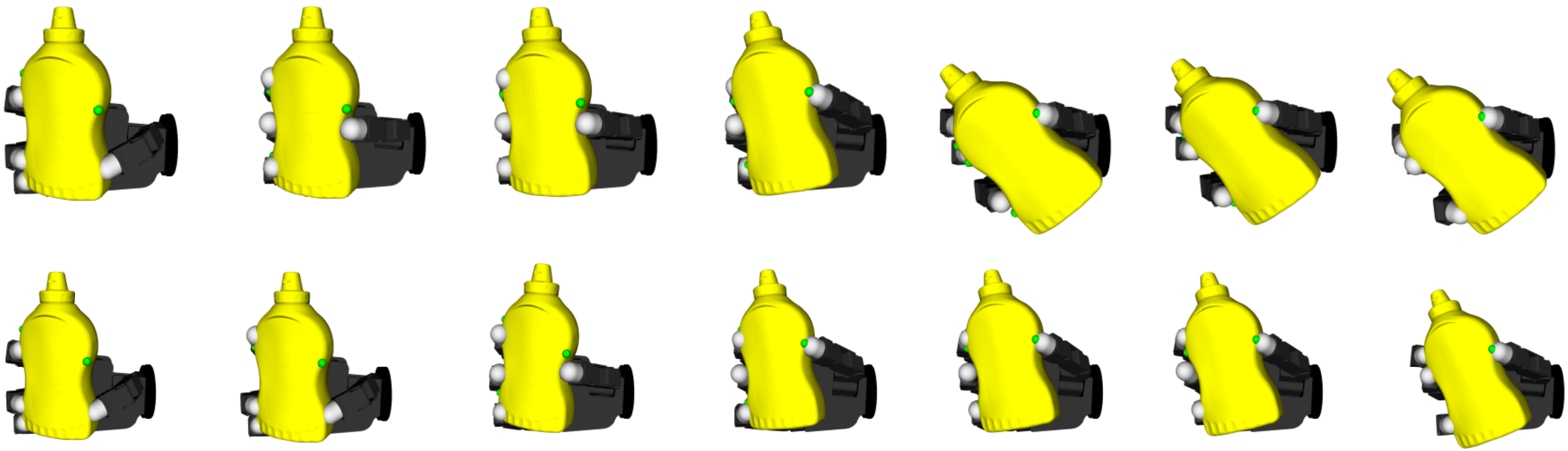
Experiments

- Planning time

Object	Method	Maximum(s)	Median(s)
Banana	SD	1025.35	902.65
	SVD	84	45
Sugar-box	SD	2283.37	1917.41
	SVD	112.59	99.38
Mustard	SD	1133.504	649.69
	SVD	135	92.83
Soft-scrub	SD	884.927	388.317
	SVD	95	74.97
Pringles	SD	3513.96	796.93
	SVD	134.275	16.0052

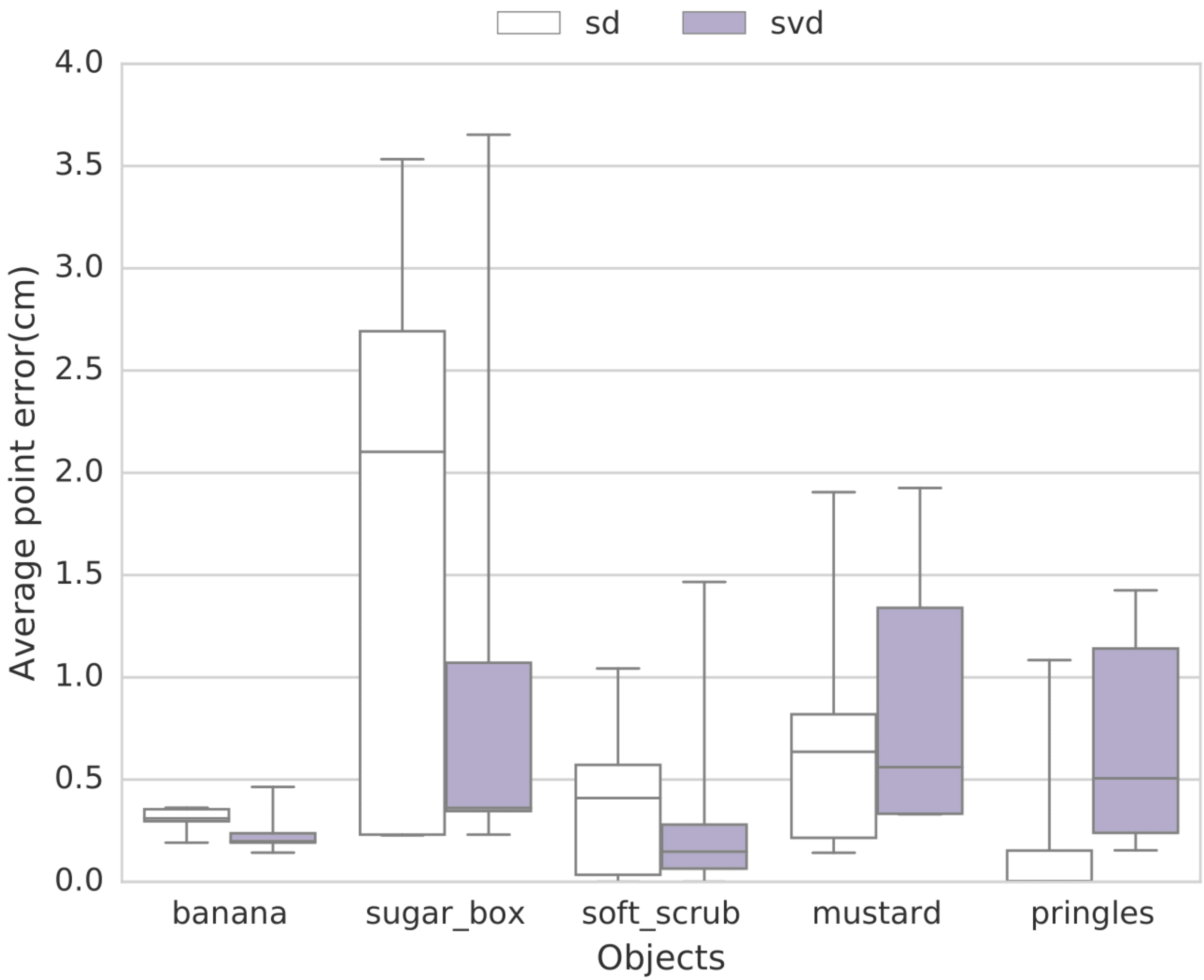
Experiments

- Different strategy



Experiments

- Average Point Error across the objects



Conclusion

- An optimization based planner that can generate collision-free plans to regrasp objects in-hand without dropping the object
- Planner builds on two in-hand manipulation primitives– finger gaiting and in-grasp manipulation– both formulated as optimization problems

Future Work

- Sensitivity to hyper-parameters
- Distance Metric
- Learning based approaches