

Grasp Optimization of Emergency Response Robot Using Contact Factor Graph

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1. Introduction

In high-risk industrial environments such as nuclear power plants, emergencies may arise where direct human intervention is either difficult or dangerous. Deploying robots in such environments can ensure workers' safety and enable rapid response. In recent years, extensive research has been conducted on the development of robotic systems for emergency response.

In emergency situations, robots are required to perform diverse manipulation tasks, such as turning valves or locking levers. However, these tasks demand more than basic path planning or motion control and the ability to reliably grasp and manipulate target objects is essential for successful operation.

This paper proposes a bilevel optimization framework for optimizing robotic grasps that enable robust manipulation. The proposed method constructs a contact factor graph (CFG [1]) that models various physical contact factors. We incorporate force closure, complementarity, friction cone and non-penetration constraints as differentiable factors, and obtain the optimal robotic grasp configuration. Our approach can be applied to various objects, ensuring robust grasp configurations, thereby greatly improving the reliability of robot manipulation in emergency situations.

2. Grasp Optimization via Contact Factor Graph

Many recent studies on robotic grasping have adopted optimization-based approaches. DexGraspNet [2] and BODex [3] introduce gradient-based optimization frameworks by defining differentiable energy functions and provide large-scale grasping datasets. However, DexGraspNet [2] relies on the strong assumption that all contact forces are equal, while BODex [3] assumes that contact points are unchanged to preserve differentiability.

To address these limitations, we propose a bilevel optimization method that utilizes CFG [1] with differentiable contact factors. Each geometry is defined as a Differentiable Support Function (DSF [4]) to make the contact factors differentiable with respect to the robot joint configuration. This formulation enables optimization without reliance on restrictive assumptions.

2.1. Differentiable Contact Factors

Our main goal is to generate a grasp configuration for arbitrary objects. To achieve this, we construct a contact

factor graph by defining four differentiable contact factors, similar to [1].

1) Force closure: A robust grasp configuration must be able to generate sufficient contact forces to resist external forces in any direction. To model this condition, we design the force closure factor as

$$c_1 = G + \sum_{i=1}^N P_i f_i = 0 \quad (1)$$

where G is the 6D external force and torque, f_i is the 3D contact force applied by the i -th finger, P_i is the Jacobian to map f_i to the force and torque at the center of mass of the object, and N is the number of fingers.

2) Complementarity: The contact force f_i and the gap g_i between the i -th finger and the object must satisfy the complementarity constraints such as

$$c_{2,i} = g_i f_i = 0. \quad (2)$$

This condition enforces that a contact force f_i is applied only when the contact occurs.

3) Friction cone: For physically reasonable grasping, each contact force f_i must lie within the friction cone K_i , centered at each contact point and aligned with each contact normal. This friction cone constraint is modeled as

$$c_{3,i} = f_i - \Pi_{K_i}(f_i) = 0 \quad (3)$$

where $\Pi_{K_i}(\cdot)$ denotes a projection onto the friction cone K_i .

4) Non-penetration: To prevent each finger from penetrating the object, we design the non-penetration condition for the gap g_i as

$$c_{4,i} = \min(g_i, 0) = 0. \quad (4)$$

2.2. Bilevel Optimization

We define an energy function that incorporates all contact factors as

$$E(q, f_{1:N}) = C_1 + \sum_{i=1}^N (C_{2,i} + C_{3,i} + C_{4,i}) \quad (5)$$

where q denotes the joint configuration, and the energy term for each factor is given by $C_j = \frac{1}{2} \|c_j\|^2$. Following [1], this energy is minimized using the bilevel optimization strategy as follows:

$$\min_q \min_{f_{1:N}} E(q, f_{1:N}). \quad (6)$$

This formulation significantly reduces computational cost, since the energy E is convex with respect to f_i for fixed q .

3. Experiments

We model the mobile manipulator with Husky A300 UGV mobile base, Franka Emika PANDA 7-DoF manipulator, and a parallel gripper. Experiments are conducted to grasp different shapes of valves and levers, and implemented in the simulation based on SubADMM [5]. We use two types of valves (disk and wheel), and a stick lever. The grippers are defined as two box-shaped DSFs, and the grasping target is defined as a specific DSF for each scenario. Our method is evaluated on the various relative position of the robot base to the valves and levers. The results of our bilevel optimization framework are shown in Fig. 1, 2, 3 and 4.

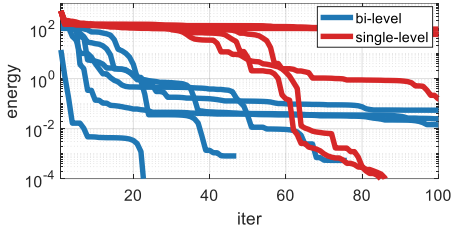


Fig. 1. Optimization using bilevel and single-level approach.

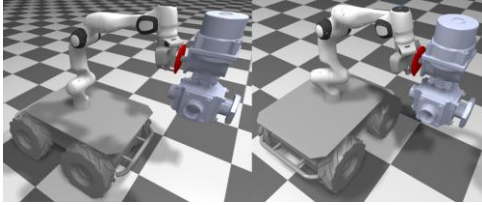


Fig. 2. Grasping a disk valve with different positions

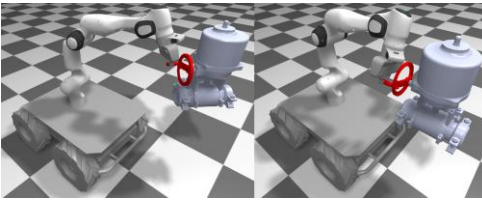


Fig. 3. Grasping a wheel valve with different positions

Figure 1 shows the optimization result for all scenarios using the bilevel and the single-level approach, which optimizes q and $f_{1:N}$ simultaneously. The bilevel approach achieves lower energy within fewer iteration than the single-level approach for all cases.

Figure 2 and 3 show the results of grasping a disk valve and a wheel valve. The handles of both valves are defined as cylinder-shaped DSFs. The grasp configuration is effectively optimized under different relative robot positions, leading to firm and stable grasps in simulation.

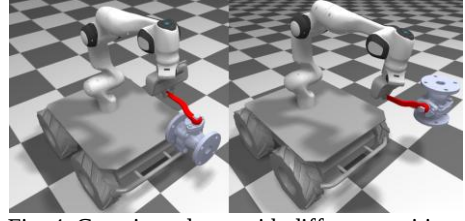


Fig. 4. Grasping a lever with different positions

Figure 4 shows the results of grasping a stick lever. The lever is defined as a box-shaped DSF. The grasp configuration is effectively optimized under the various lever angles and the relative robot positions, leading to firm and stable grasps in simulation.

4. Conclusion

We propose a bilevel optimization framework using a contact factor graph for optimizing robotic grasp configurations. We define four differentiable contact factors such as force closure, complementarity, friction cone, and non-penetration constraints, and incorporate them into an energy function. The bilevel optimization strategy minimizes the energy function efficiently and robustly generates grasp configurations. This framework enables more stable robot manipulation, contributing to more reliable robotic response in emergency situations.

Future works can include additional contact factors considering contacts generated by robot links except the grippers, or positional constraints for the robots.

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