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Emergency Response Robot Motion Optimization using Complementarity Constraints

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1. Introduction

In nuclear power plants, emergencies can arise that are difficult or dangerous for workers to respond. In such situations, utilizing robots is crucial to ensure human safety and mitigate the risk of escalating into major disasters. Currently, various research groups are conducting studies on nuclear disaster response robots. These studies aim to explore ways in which robots can perform tasks in place of workers during emergencies and minimize the risk of accidents.

A key challenge here arises from dealing with phase transitions. For instance, in a door-opening operation, the robot must first navigate to the door, and then switch phase to grasp the handle and pull the door open, each phase requiring distinct strategies.

This paper presents research on motion generation for various emergency situations (i.e., valve turning, lever locking, door opening) based on optimization. We propose an optimization framework that effectively considers mode switching using the complementarity condition. Through this framework, we successfully achieve robot motions to enhance emergency response capabilities in nuclear power plants.

2. Optimization-based Motion Generation

The motion generation problem is generally modelled as an optimization problem, and there exist various packages for this purpose such as MoveIt [1], TrajOpt [2]. These packages primarily focus on planning paths to designated target points, while avoiding collision. They exhibit limitations in complex tasks involving changes in motion phases due to contact or other factors.

To address these switchings, it is possible for users to explicitly specify the sequence of tasks or conduct high-level task sequence planning separately from low-level motion planning. However, when optimizing by separating modes in this manner, it becomes problematic that task planning considering low-level motion is not feasible, and the influence between modes cannot be considered.

We propose an optimization formulation based on complementarity conditions that implicitly considers switching between modes to solve this problem and generate more autonomous and natural motion.

2.1 Optimization Formulation

Our goal is to optimize the motion of 7-DoF manipulator to perform tasks of 1) pressing button, 2) opening door, 3) turning valve, and 4) locking lever.

The optimization formulation is as follow:

$$(1)\quad \min_{X} f_{goal} + f_{traj} + f_{col} + f_{comp}$$

where, $X = \{x_1, \cdots, x_N, \xi_1, \cdots, \xi_N\}$ is the set of waypoints, $x_i \in \mathbb{R}^7, \xi_i \in \mathbb{R}^{n_\xi}$ is the i-th waypoint of the manipulator and target object respectively, n_ξ is the degree of the freedom of each object, N is the number of waypoints, and $f(\cdot) \in \mathbb{R}$ is the objective functions. Each objective functions are composed as follows.

1) **Goal performance**

   To make the target object (i.e., door, valve, lever) to reach the goal position, goal performance objective function is defined as:

$$f_{goal} \coloneqq \frac{1}{2}\left\|\xi_i - \xi_{goal}\right\|^2$$

   where $\xi_{goal} \in \mathbb{R}^{n_\xi}$ is the goal position of the object.

2) **Path length minimization**

   To minimize the length of the distance between adjacent waypoints, path length minimization objective is involved. The objective is as follows.

$$f_{goal} \coloneqq \sum_{i=1}^{N-1} \tfrac{1}{2}\|x_{i+1} - x_i\|^2 + \tfrac{1}{2}\|\xi_{i+1} - \xi_i\|^2$$

3) **Obstacle Avoidance**

   Obstacle avoidance objective enforces the robot to not collide with the target objects:

$$f_{col} \coloneqq \mathcal{I}(g_{col}(x_i, \xi_i) \geq 0)$$

   where $\mathcal{I}(\cdot)$ is an indicator function, $g_{col}(x, \xi) \in \mathbb{R}$ is the signed distance from object with state ξ and the manipulator with state x.

4) **Mode switching**

   The mode switching objective imposes a condition where the object can move only when the distance between the target and the robot is zero, ensuring that the target object does not move when there is no contact between the target and the robot.

$$f_{comp} \coloneqq \mathcal{I}(g_{work}(x_i, \xi_i)(\xi_{i+1} - \xi_i))$$

   where $g_{work}(x, \xi)$ is a distance between robot and object, calculated considering the characteristics or each task.

Note that the optimization formulation (1) offers flexibility to incorporate additional optimization variables or objective functions if needed.

3. Implementation

We modeled the manipulator with Franka Emika PANDA 7-DoF manipulator, and a 1-DoF parallel gripper. Subsequently, we perform optimization using the proposed optimization formulation with SubADMM [3] for valve turning, lever locking, and door opening tasks. The motion was initialized that the robot arm and target object remain stationary, and do not touch each other. With our framework, it was possible to achieve optimal motion without extensively focusing on initialization or by heuristically defining the phases. Based on the optimized results, we conduct dynamic simulations to verify the successful execution of the tasks.

3.1 Valve Turning Module

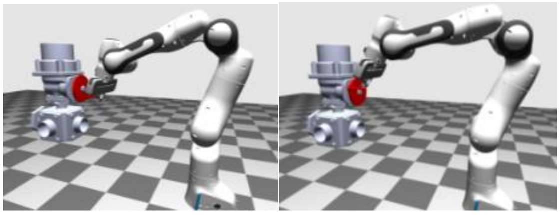

Fig. 1. Simulation snapshots of valve turning task.

The distance g_{work} is defined as the distance between the handle of the wheel and the robot end effector. The valve turning example also could be successfully performed using our framework.

3.3 Lever Locking Module

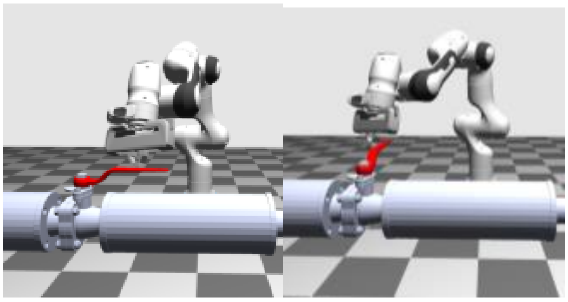

Fig. 2. Simulation snapshots of lever locking task.

The distance g_{work} is modeled as the distance from the robot end effector to a specified point on the lever. The lever locking could be successfully done using the generated motion in our simulation..

3.2 Door Opening Module

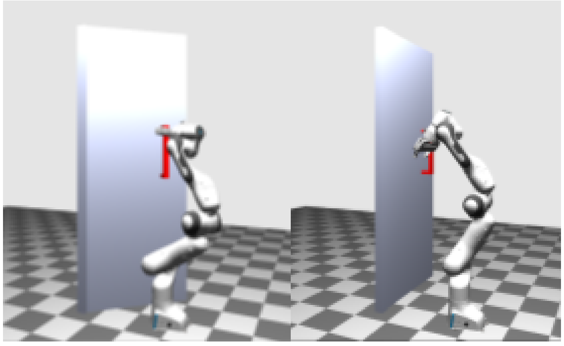

Fig. 3. Simulation snapshots of door opening task.

For the door opening module, the distance between robot and the door is defined as summation of the Euclidean distance between the handle and the robot, and the distance between the direction of the handle and the direction of the robot's end effector. As a result, the robot hand slides within the handle for better configuration while opening the door, as shown in Fig. 3.

4. Conclusions

We propose the optimization-based motion planning framework for emergency response robot using complementarity conditions. Utilizing the complementarity conditions enable us to facilitate transitions between different phases, resulting in more natural motions. Using the generated motions, we could successfully complete the valve turning, lever locking, and door opening tasks in simulation. Our future work includes optimization of motion that involves transitions between multiple, more complex phases.

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