**REPURPOSING A SAMPLING-BASED PLANNER FOR A SIX-DEGREE-OF-FREEDOM MANIPULATOR TO AVOID UNPREDICTABLE OBSTACLES**

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***ABSTRACT:***

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1. **INTRODUCTION**

Robot manipulators such as industrial robots work well in repetitive and heavy tasks. They are high-performing, objective, and relentless at task that are too difficult to complete by an operator or a group of workers. However, given their rigid and massive construction, even a small-sized industrial robot impose significant hazards on the people that work near it. Hence, recently, robot manipulators are more compliant and are designed to work with workers cooperatively without risking their safety [1]⁠. Regardless, it is still an issue of hazard should a compliant or cooperative robot collide with a person working at close to its workspace [2]⁠. The collision also warrants expensive maintenance and repairs. To address a more intelligent motion and, evidently, a safer motion planning, an industrial robot system implements a certain degree of planning algorithm specifically for the motion of the manipulator.

A robot motion planner provides a collision-free motion solution for a manipulator. Here, a solution is defined as collections of waypoints or trajectories. In the case of the traditional definition of industrial robots, the planning is global because the robot is enclosed and isolated in workcell. A global planner takes in a set of initial and goal positions, , or as set of initial and goal poses, , as its input and generates constraint-informed trajectory as intermediate waypoints for the robot to follow. However, a global planner is offline, which implies that the trajectories are set before the task commences. The global planner also assumes a static workspace. Any unplanned changes in the workspace over the global planning-scheme, such as an unplanned introduction of a stationary object or a moving object into the robot workspace, renders the offline-planned trajectory outdated and, consequently, requires replanning. In the case of a compliant robot, unplanned changes are unavoidable.

Hence, it is imparative for a compliant manipulator or cooperative manipulator to have an efficient motion planner because replanning is computationally expensive and time-consuming; sampling-based planners are the pinnacle example of efficient planning [3]⁠. Unfortunately, sampling-based planner trade completeness and optimality with efficiency where the planner may fail to provide a solution [4]⁠. Also, if a solution exists under its metric space, the waypoints may not be the least cost path to a goal [5]⁠.

Regardless of lack of completeness and optimality, sampling-based planner excel at maintaining reasonable usage of computational resources that pave way to the near-online planning scheme. The sampling-based planners for robot motion are a family of planners that uses probabilistic approach to generate a graph structure encoding the free space and the robot configuration space. The sampling are stochastic, such that resampling will give a unique solution to the previous sampling. Most sampling-based planner are also tractable in higher-dimensional configuration and task space. However, sampling-based planners assume static workspace.

This paper repurposes the use of sampling-based motion planning, the rapidly-exploring random tree motion planning, to address operation task in a dynamic environment in Euclidean space, $$. Our method leverage the efficiency and the computationally reserved sampling-based motion planning without needing to apply purely reactive motion planning approach so that computational resources can be delegated to other tasks, i.e., motion-tracking, state estimation, mapping, localization, and motion control. In the following of this report, we will assume sampling planners provide solution in higher dimensional configuration space, which implicates a solution with a set of poses represented by the special Euclidean group, $$. This paper is a part of a collision avoidance system for a compliant robot manipulator design to prove an encoderless concept, and only cover the formulation of the planning approach we adopt for our robotic system.

1. **RELATED WORK**

Kavraki et. Al (1998) is the first group of researchers that used probability model for sampling the configuration space for holonomic robot motion such as a manipulator robot [4]⁠. The planner are called the probabilistic roadmap (PRM) motion planning. The algorithm construct a graph structure to find path between an initial pose to a goal pose in two-dimensional configuration space, $$. Kavraki et. al (1996) also proof a more general solution for higher dimensional configuration space, $$. With graph structure, more than one path connect the initial pose to the goal pose. Therefore, PRM is a multi-query type planner.

Kunz et. al (2010) improve PRM by redefining the distance metric of a robot manipulator so that the robot can move around a moving obstacle in real-time. Their approach performs well in an uncluttered environment [6]⁠. They also redefined the distance function of the PRM to address dynamic objects, such as a walking person, into a two-dimensional map. Although the configuration space of the manipulator is in $$, the map, constructed from a two-dimensional LiDAR scan, is in $$.

In retrospect, the RRT was formulated for non-holonomic motion targeting problems addressed in diffential-constrained motion such as a car on a plane [5]⁠. However, given the model of its metric space and consequently the configuration space, RRT are tractable for higher dimensional problem such as manipulator motion in 3D space \parencite{Wei2018}[7]⁠. RRT assume as static environment but Wei & Ren (2018) successfully change the way RRT samples a robot metric space so that it is fast enough to react with a changing environment. Also, unlike PRM, RRT works well in a cluttered environment because of the randomized sampling on the robot configuration space in the metric space.

Unlike the works in [8]⁠and [7]⁠, so few have applied their planning algorihtms on a robot manipulator despite both algorithms provides mathematical framework for planning for multi-body and multi-frame system. In this paper, we will use the method demonstrated by Kunz et. al (2010) and Wei & Ren (2018) to design our experiment of a moving obstacle collision avoidance with the implementation of the vanilla RRT to solve motion for robotmanipulator in three-dimensional space, $$. Different from the implementation by Wei & Ren (2018) our method implement the vanilla RRT where we do not represent the obstacle configuration space.

1. **FORMULATION AND ALGORITHMS**

This paper will use the superscript notation to refer the control space and the subscript as the equivalent representation in the configuration space. For example, $$, refers to the control space of the end-effector where the controlling pipelines would take in $$, and the equivalent pose is in the configuration space, $$. Since, revolute joint topology is the 1-hypersphere, $S^1$, we will assume that, for the case of 6R robot, it's joints are limited to a certain range which makes $$.

* 1. **The Geometry of a Compliant Robotic Arm, *r\_mini***

We prototype and build a 3D-printed robot called Richard Mini (*r\_mini*, see Fig. 1) based on the conditioned addressed by \textcite{Pieper1968}, which entails three collated joints sharing the same cross point of their $$ shown in Fig. 2.

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| (a) *r\_mini* hardware assemblage | (b) r\_mini CAD design |
| Figure1: A 3D printed compliant manipulator, *r\_mini*, are designed to replicate a common industrial robot construction | |