Toward the Design and Control of a Robotic System for Autonomous Solution Mixing

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Abstract

Many industries are increasingly implementing autonomous robots to streamline simple and monotonous processes and keep human operators safe from harm during the task they are performing. Hazardous chemical experiments, which have resulted in casualties, have yet to incorporate robotic manipulation to keep experimenters from harm. The proposed work conducts a randomized Monte Carlo simulation of different end-effector configurations of a standard Universal Robot 5 (UR5e) arm and observes the feasible workspace region and singularities that arise. The results presented in the proposed work can help identify whether a UR5e arm can perform standard chemistry lab-related tasks such as pouring and mixing beakers and flasks.

Introduction

Automation and robotics have been steadily integrated into various fields, including healthcare [1][2], e-commerce warehouse shipments [3], and manufacturing or industrial applications [4]. This is due to the work requiring long hours and a high degree of precision while maintaining safety from hazardous objects and dangerous movements. The Universal Robot 5e (Universal Robots, Odense, Denmark), or UR5e, is commonly incorporated to automate the tasks mentioned above as a relatively cheap and scalable solution. Additionally, the UR5e is commonly marketed as a 'cobot' for its ability to work in tandem with humans to mutually improve efficiency. With six degrees of freedom (DoF), the UR5e can reach various positions and orientations in 3D space. The six revolute joints result in a large workspace volume for flexibility and adaptability in the tasks that the UR5e robots are used for, such as moving objects from one location to another [5].

Chemical experimentation labs, in which hazardous materials and solutions are handled, are another problem space that may benefit from UR5e manipulation and automation. Lee et al. [6] reported 30 chemical accidents over a three-year period, with 22 related to hazardous chemical substances. 21 cases of the 30 reported were attributed to experimenter carelessness, which could be solved with robotic and automated movement and planning. Van Noorden [7] reports experimenter casualties in a chemistry lab setting, where a student at Texas Tech was grinding nickel hydrazine perchlorate in excess amounts, which detonated. The experimenter lost three fingers on their left hand due to the accident. Had a human-controlled robotic arm interacted with the perchlorate, no human arms would have been lost, and only the robotic arm would have been damaged.

The proposed work will observe and assess the feasibility of using UR5e robots in chemical lab settings to prevent any accidents that may lead to injury of the experimenters. The robot arm will pick up cups that will carry a solution, pour two of the cups into a mixing cup, then rotate the mixing cup in two axes to emulate a stirring motion. The task is first modeled in simulation, then implemented in the real world. A workspace and singularity analysis of the UR5e robot is also demonstrated in simulation to observe whether the physical constraints of the robot will suffice for chemistry experimentation applications.

The proposed simulation incorporates components of the workspace analysis done of the UR5e by Niu et al. [5] and the singularity analysis of a two-link robot by Stejskal et al. [8].

Methods

The MATLAB Robotics Toolbox and the Robotics System Toolbox Robot Library Data was used to simulate the UR5e robot. These toolboxes possess pre-built URDF files of the UR5e that can be visualized using the *interactiveRigidbodyTree* function, as shown in **Fig. 1(a).** A Monte Carlo simulation (*n = 1000, 5,000, 10,000)* of randomized robot poses was used to populate the different end-effector positions that were then labeled as either a feasible workspace orientation or a singularity. To determine the singularity, the absolute value of the determinant of the Jacobian from the robot base to the end-effector was calculated and assessed. A singularity coefficient, *S*, was determined to create a threshold of Jacobian determinants indicating a singularity, ranging from 0 to k. The decision algorithm is depicted in **Fig. 1(b)**. The end-effector pose was then plotted in a 3D scatterplot and color-coded to differentiate between a feasible configuration or a singularity as black or red, respectively.

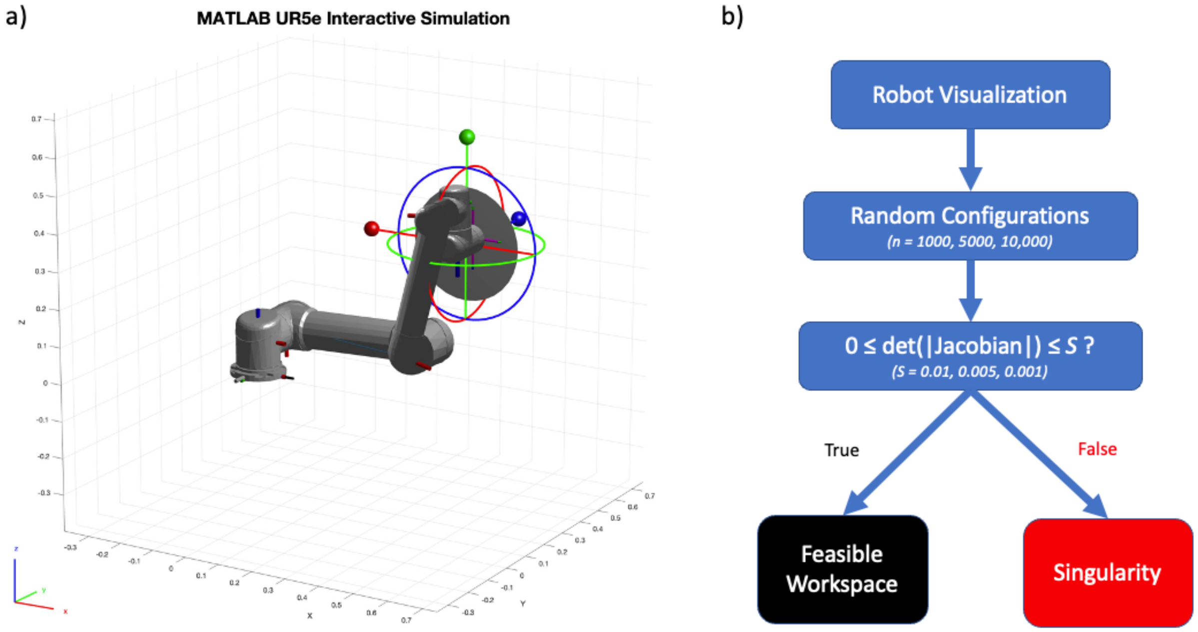

Fig. 1 a) UR5e Interactive Rigid Body Tree from MATLAB Robotics Toolbox. b) Algorithm proposed to determine whether Monte Carlo random configurations are feasible workspace points or singularities.

The number of random configurations varied between 1,000, 5,000, and 10,000 to observe if there were any differences in observable results that are dependent on the number of simulation cases. The configuration number is also compared to the time it takes to complete each simulation to evaluate the trade-off between more data and less computation.

The singularity coefficient, *S*, was varied from 0.01, 0.005, and 0.001 to determine the appropriate *S* required to obtain the most accurate representation of the "singularity space." For each simulation, the number of singularities found was recorded, and the percentage of singularities per simulation was calculated and recorded to observe the trade-off between the loss of feasible workspace configurations and a tighter singularity threshold.

Results and Discussion

The respective point clouds for each of the three trials are shown below in Figures 2,3, and 4. The trials' singularity coefficients, S*,* and corresponding error percentages are tabulated in Table 1. The point clouds indicate that, as more configurations are tested, there is a clear workspace volume visible despite occasional singularities.

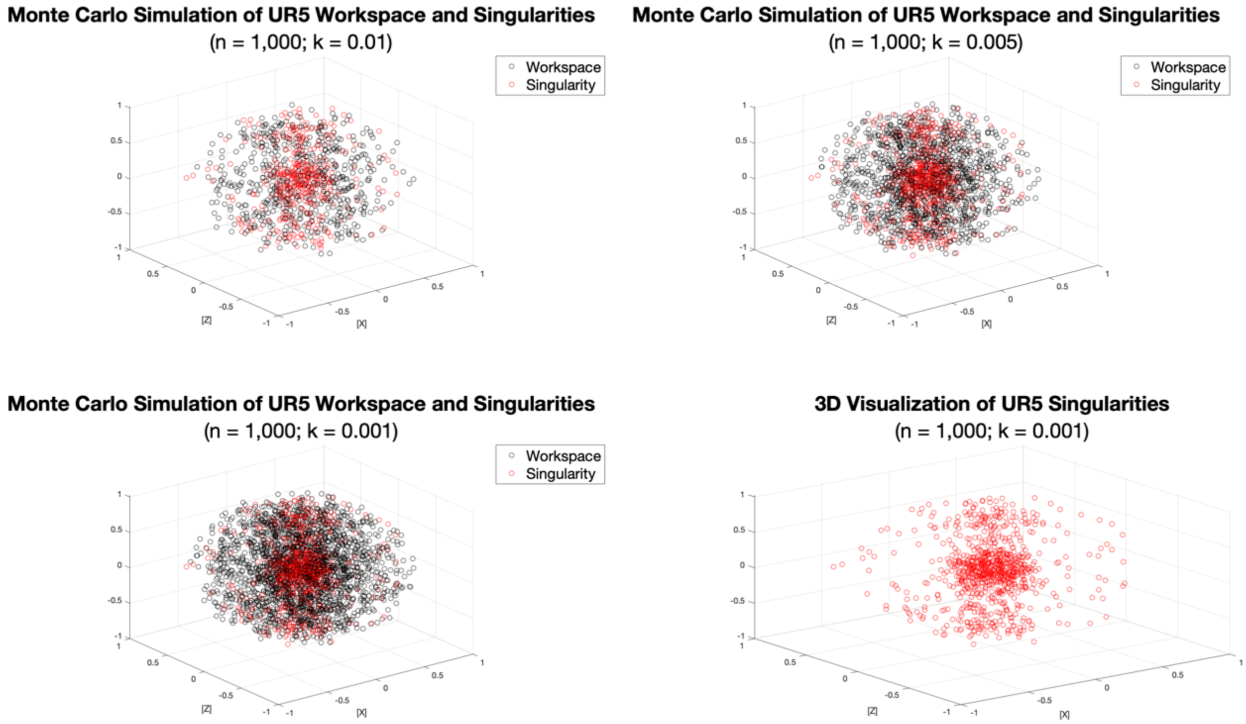

Fig 2. Monte Carlo simulation results with 1,000 different configurations for each *k* value.

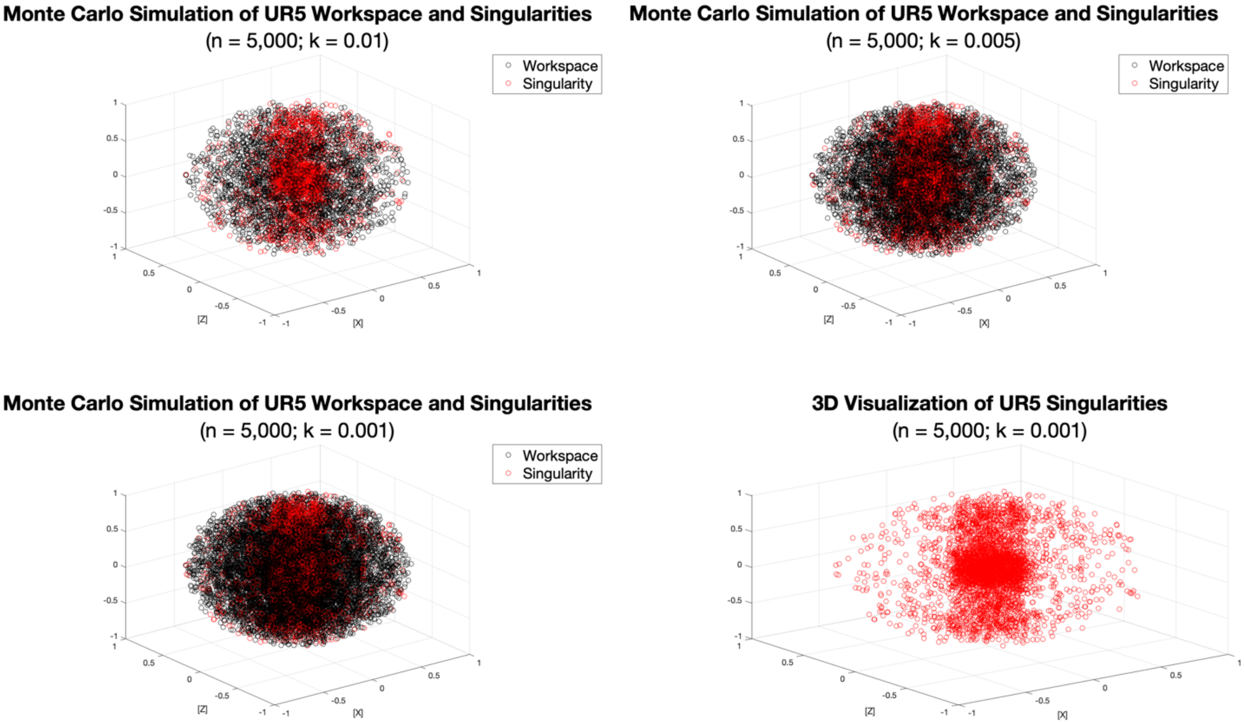

Fig 3. Monte Carlo simulation results with 5,000 different configurations for each *k* value.

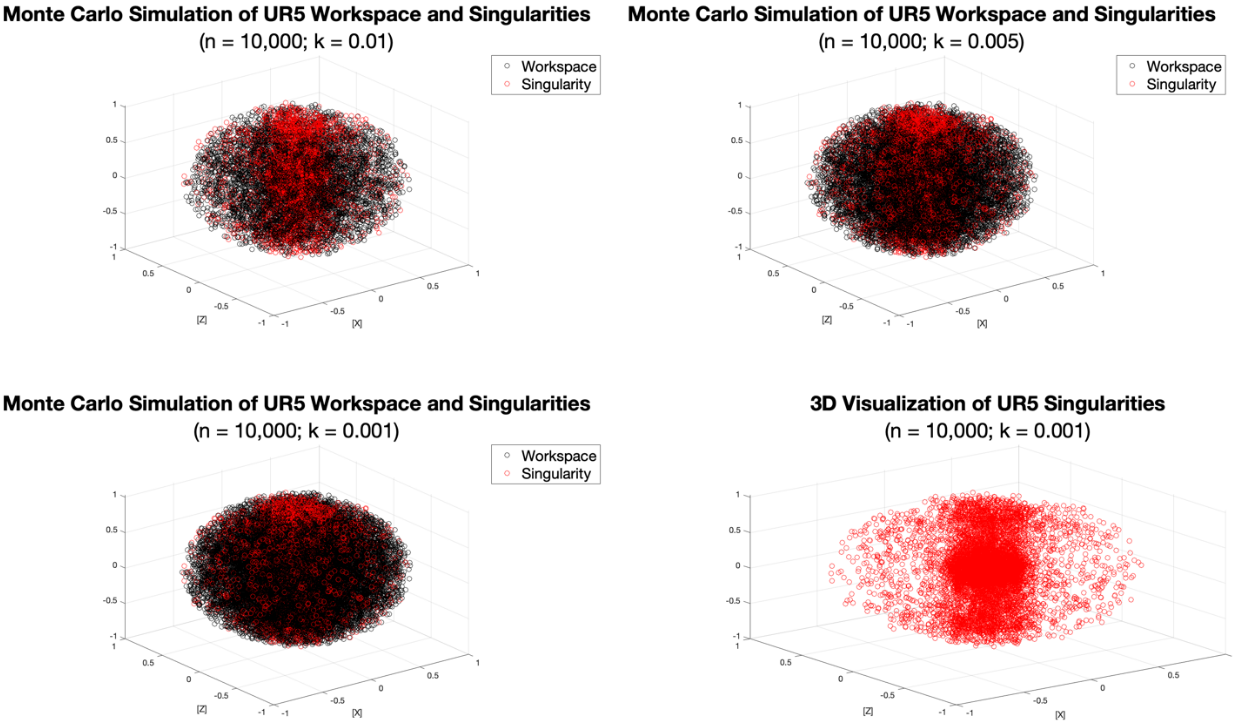

Fig 4. Monte Carlo simulation results with 10,000 different configurations for each *k* value.

Table 1. Percent (%) singularities observed with varying Singularity Coefficients, *S*.

# Simulations	*Singularities (%)*		
	***S* = 0.01**	***S* = 0.005**	***S* = 0.001**
1,000	42.10	27.70	12.20
5,000	42.12	29.00	12.62
10,000	42.08	30.52	12.25

The data presented in Table 1 show two noteworthy trends. As *S* decreases, the number of configurations labeled as singularities decreases. This is a reasonable result, as the threshold of what is determined as a "singularity" decreases as *S* decreases. In addition, the number of simulations completed has no significant effect on the distribution of singularities observed within the same *S*. The time taken to complete the simulations is also reported in Table 2:

Table 2. Time taken (sec) to complete three simulations of varying sample size

# Simulations	Trial 1	Trial 2	Trial 3	Average
1,000	1.1299	0.9657	0.91445	1.0034
5,000	4.8325	4.6426	4.5907	4.6886
10,000	9.3437	9.1429	9.1716	9.2194

Despite the greater number of simulations, all calculations required less than 10 seconds. Thus, the number of simulations can be increased for more data without significantly increasing the computing time required.

The trials revealed that the furthest point the UR5e robot can reach is approximately 0.817 m from the robot base. Given that this is the robot's workspace, the inherently smaller task space dictates that the robot can, at maximum, interact with and move a beaker within slightly less than 1.634 meters in radius about the robot base. The cylindrical space in the center of the figures above represents the singularities that arise when the robot joints overlap. However, for this scenario, all solutions will be grasped, poured, and mixed above an adjacent table surface outside of this cylinder, utilizing the distal end of the workspace. Provided the robot does not reach the potential joint-lock configurations (including but not limited to the red points in the above figures), chemical solutions can be manipulated in any desired manner.

Conclusion

A workspace and singularity analysis of the UR5e robot arm was conducted to assess the feasibility of incorporating the UR5e into chemistry lab settings to automate the handling and mixing of hazardous fluids. The results not only showed that the proposed robotic arm can be utilized in chemistry lab settings, but the data obtained also shed light on appropriate parameters for simulations on singularity configurations. A ten-fold increase in the number of simulations (1000 to 10,000) does not significantly increase the computation time required to complete a singularity analysis. This will allow future simulations to have more than 10,000 random configurations, which can provide more data. To add, the singularity coefficient will ideally be as close to 0 as possible for a tighter threshold for determining what configurations are singular. Future work includes the physical implementation of the Monte Carlo simulation to determine the numerically exact singularity points given any random configuration. The proposed work will also lead to testing and evaluating the UR5e arm performance of physically moving beakers with solutions, pouring the solutions into empty beakers, and mixing multiple solutions within a single beaker.

References:

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