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Revision 0

Development of Semi-Autonomous Robotic Manipulator for Off-Riser Sampling of Tank Waste

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
Office of River Protection under Contract DE-AC27-08RV14800

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Date Published
December 2022

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SUMMER INTERNSHIP TECHNICAL REPORT

Development of Semi-Autonomous Robotic Manipulator for Off-Riser Sampling of Tank Waste

DOE-FIU SCIENCE & TECHNOLOGY WORKFORCE DEVELOPMENT PROGRAM

Date submitted:

December 27, 2022

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Submitted to:

U.S. Department of Energy
Office of Environmental Management
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FIU | Applied Research Center
FLORIDA INTERNATIONAL UNIVERSITY

EXECUTIVE SUMMARY

This research work has been supported by the DOE-FIU Science & Technology Workforce Development Program, an innovative program developed by the U.S. Department of Energy's Office of Environmental Management (DOE-EM) and Florida International University's Applied Research Center (FIU-ARC). During the summer of 2022, a DOE Fellow intern, Joel Adams, spent 10 weeks doing a summer internship at Washington River Protection Solutions in Richland Washington under the supervision and guidance of Dr. Douglas Reid. The intern's project was initiated on June 5, 2022, and continued through August 11, 2022, with the objective of developing a robot manipulator to demonstrate semi-autonomous off-riser sampling of tank waste.

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1. INTRODUCTION

Hanford's underground tanks hold waste from over four decades worth of plutonium production. The Washington River Protection Solutions (WRPS) operates the tanks for the Department of Energy's Office of River Protection (ORP). In this mission, WRPS stores, monitors, and retrieves along with transferring the waste for treatment. To support the mission, WRPS must sample the waste at various steps in the process.

One key step is during the post-retrieval, which is driven by the need to assess the hazard of waste left in the tanks. It is critical to obtain samples to support the data quality objects for closure of the tank. The remaining waste may not be readily available under existing risers and as such has created the need to develop off-riser sampling. Off-riser sampling of waste tanks is a challenging task because access ports are limited, and the tank floor is deep underground.

This report presents a feasibility study of using a robotic arm deployed through a small diameter riser in tanks to sample residual material at the bottom of a retrieved single shell tank. The study uses an existing Universal Robot 6 degree of freedom arm in the evaluation of different concepts and explores options for the deployment and retrieval of samples. Finally, the report provides a path forward for future study.

The UR5e robot manipulator was equipped with a depth camera to allow the incorporation of computer vision solutions. The depth camera utilized is an Intel RealSense D455, which allowed for disparity images to be converted into point cloud data. The data was analyzed with probabilistic grid using the Octomap library. Multiple approaches are investigated that optimize the stability of the arm. This includes having it operate upside down and having it deployed right side up on the bottom of the tank.

These demonstrative capabilities serve as a valuable proof-of-concept of off-riser sampling using autonomous systems that make use of state-of-the-art algorithms and integrate various sensor data. The eventual deployment of such technology would allow for updated and reliable waste data from tanks to be collected in a cost-effective and safe manner, which will allow for decisions to be made during tank closure operation of the Hanford tanks.

2. HARDWARE AND SETUP

A robot was developed to simulate the sampling of tank waste. This task poses numerous challenges, which the proper selection of platform and sensors can aid in resolving. The main platform utilized is a robot arm from Universal Robotics called the UR5e, a model containing joint torque information. The platform is robust and allows for integration of outside control while keeping safety mechanisms in place at the top software level. This feature ensures that any bugs in the written code can't result in destructive behavior.

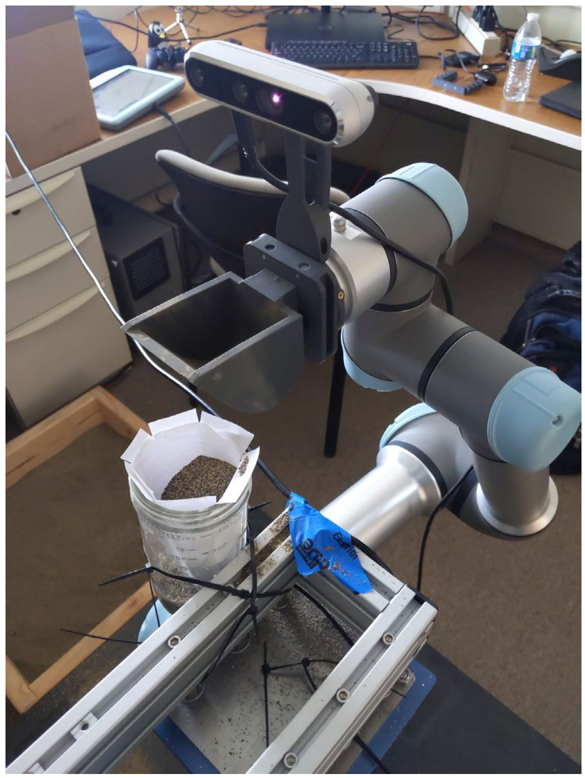

Figure 1. UR5e manipulator with attached hardware and sensor setup

A Linux laptop running a Debian-based distribution was used to develop software, communicate with, and visualize data from the UR5e manipulator. This system was connected to the same network via Ethernet attached to the robot's control box. An outside host, in this case, the laptop was granted access to send and receive information via the pendent that comes with the UR robots. The outside control allowed for the use of the Robot Operating System 2 (ROS2), a middleware that serves as a message passing system as well as a tool for integrating a plethora of useful robotics code libraries and state of the art algorithms via developed packages. Another benefit of using ROS2 is the ease of integration of additional sensors such as a depth camera for perceiving the environment. The sensor used for this feature is an Intel RealSense D455, which was mounted on the end effector of the robot and is further discussed in the next section of this report.

In addition to the depth sensor, a passive scoop end effector was developed to allow for the collection of waste samples using a simulant inside of a test bed. A mechanical system was also created to allow for the robot to be mounted upside down to simulate being lowered down into a tank via a riser. The mounting device allowed for the height of the robot from the floor to be adjusted, a crucial variable to experiment with due to the changes in workspace geometry at different values. A collection jar was placed at the top of the mount above the base of the robot, a location both convenient for the manipulator to reach and a realistic option for a platform lowered into a tank from a small riser.

Figure 2. Full hardware setup for off-riser sampling with UR5e in extended position

The overall hardware setup enabled the UR5e robot to perceive the environment, have workspace flexibility, and demonstrated as a proof of concept the task of using a robot manipulator to perform off-riser sampling of tank waste. The next layer of work was the software side of the project. Existing software libraries exist for robot manipulators such as Moveit2 which gives the developer advanced levels of control while utilizing modern manipulator kinematic theory. Further, software is available that utilizes the depth camera used and provides tools for point cloud development. All these separate software libraries were married together using ROS2 thanks to the standardization of message types for common robot applications. In the next section, environmental mapping using the Intel depth camera is discussed in more detail.

3. ENVIRONMENT MAPPING

The previously mentioned depth camera, the Intel RealSense D455, was used to provide awareness of the environment in the form of a point cloud. This point cloud is derived from the disparity images created with the use of two cameras with a physical offset between them. This provides the developer with a 3D representation of the immediate surrounding environment with a distance of one meter from the camera. Although the depth camera can capture further distances, one meter was selected due to increased distortion present at further distances.

The usefulness of having an awareness of the robot's surroundings is that it can ensure the robot doesn't collide with itself unless explicitly instructed to. The Moveit2 software library, which is further discussed in the next section, has a plugin to allow for point cloud integration so that this goal can be realized. The output of this plugin is an Octomap representation of the environment. Octomap is a probabilistic tree representation that filters out dynamic (moving) obstacles such as people and is integrated into the Moveit2 library. The map was discretized into voxels of a larger size than the original point cloud since the collision calculations using the original point cloud would be immense enough that the task would become intractable.

The point cloud was additionally used to fine-tune the transform representing the physical placement of the depth camera on the robot's end effector. Figure 3 shows this strategy being used with the aid of visualization software Rviz2.

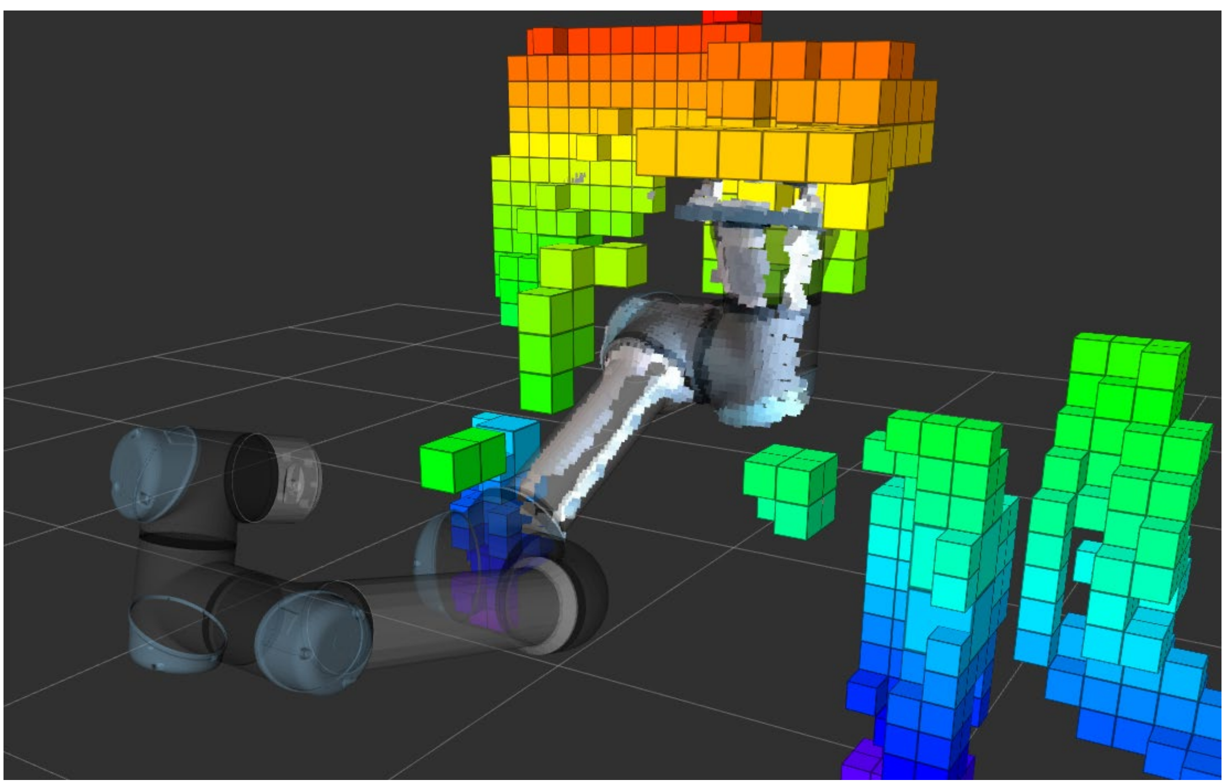

Figure 3. UR5e visualized in Rviz2 software showing an Octomap grid and a point cloud of itself overlapping with the digital model

The live data coming from the depth camera has limited utility for object avoidance due to its limited field of view and range. Thus, a program was written that instructs the robot arm to perform an initial mapping of the environment by swiveling at its base in a tucked position seen in figure 5. The result is a map with greater utility that is used when planning future trajectories. The original point cloud would still be used to aid an operator in visualizing the environment. Such an example of this is shown below in figure 4.

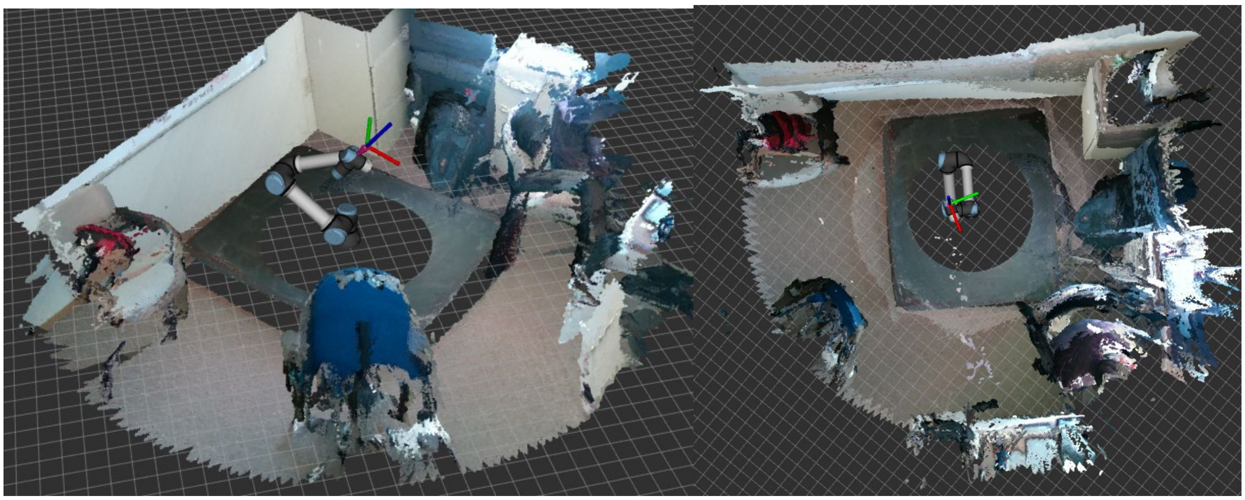

Figure 4. Isometric view (left) and aerial view (right) of point cloud representation of surrounding environment

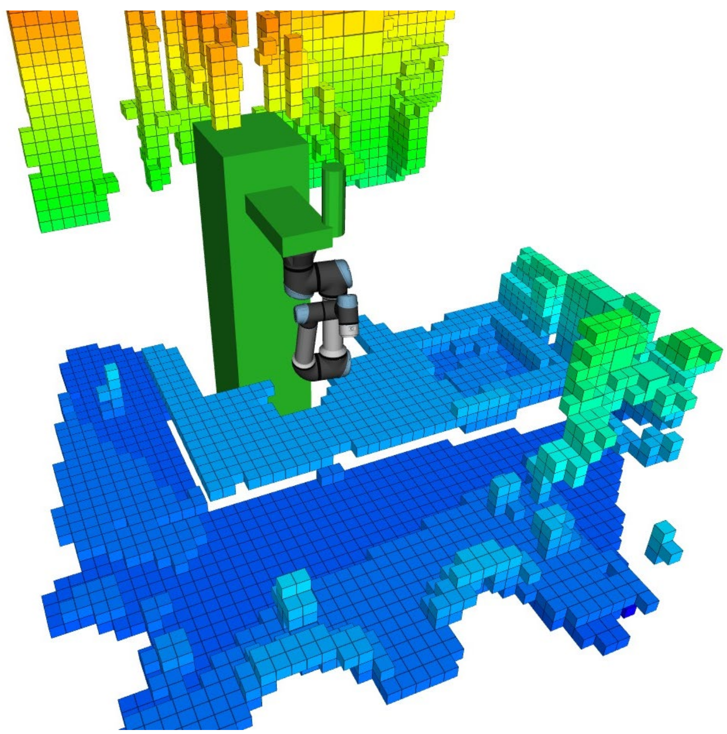

Figure 5. Rviz2 view of platform with programmed collision objects in green and Octomap of environment colored based on z-axis

4. SCOOPING ACTION DEVELOPMENT

For the robot to interact with the world, it is necessary to plan trajectories which don't encounter singularities nor collisions. This is an advanced task of which many algorithms exist in literature that attempt to tackle the various obstacles that occur with it. The Moveit2 library utilizes some of the state-of-the-art algorithms to make these goals more achievable through a programming API. The major concept of this library is laid out in figure 6 below.

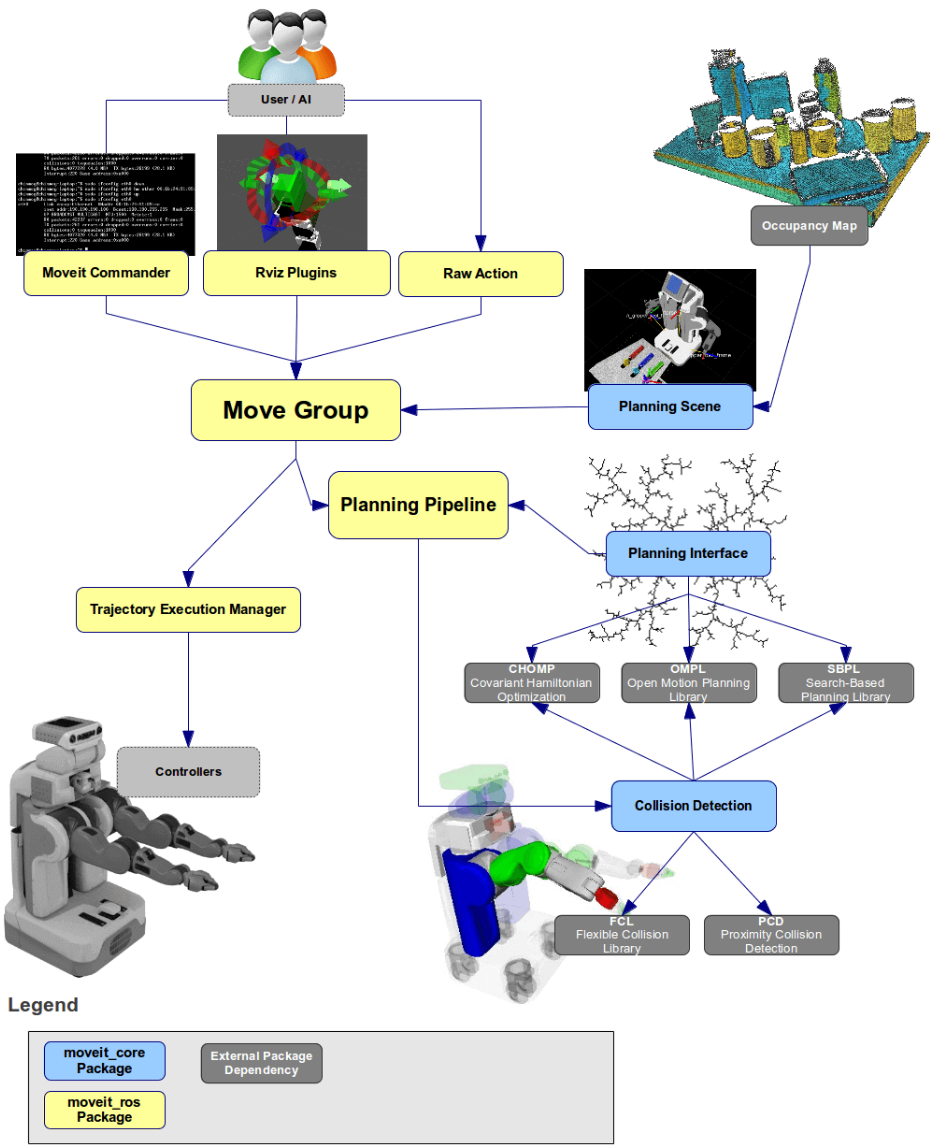

Figure 6. Moveit2 Library major concepts pipeline

The user has the option with the library to input raw actions such as trajectory goals in the joint space (forward kinematics) or Cartesian space (inverse kinematics). The move group node handles the planning and execution of trajectories and contains a high level of flexibility. There is a selection of planners available that can be used, of which, the Open Motion Planning Library (OMPL) was selected.

The planning scene object contained both collision objects that can be manually placed, as well as the Octree (the tree created by the Octomap library) both of which are visible in figure 5. With all this information, the software computed an allowed collision matrix (ACM), which is the most computationally heavy portion of the software. Its completion was an important part of the project. In this specific application, both goals in the joint space, velocity space, as well as in Cartesian space were used to command the platform to perform the initial mapping and then take a sample from the test bed. Once one of these goals were passed to the move group node, a valid trajectory was calculated, and the trajectory processing routine was used, which uses time parameterization to ensure a trajectory is always within the set acceleration and velocity constraints for all the joints.

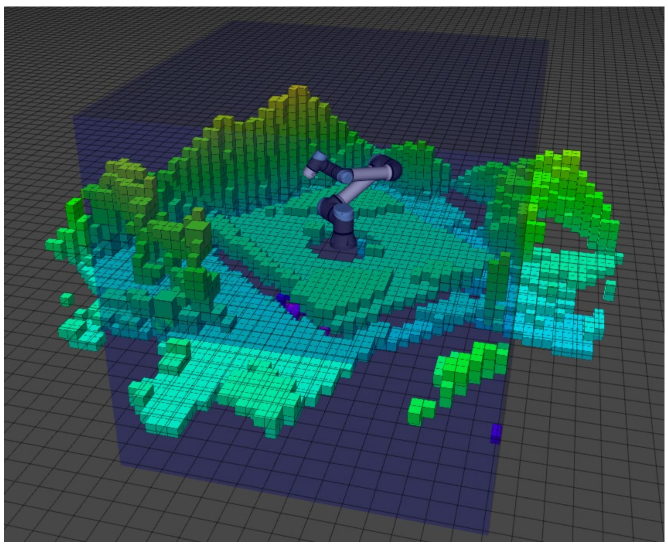

Figure 7. Robot visualizing environment after mapping with Octomap data shown as cubes and workspace of UR5e robot shaded in blue

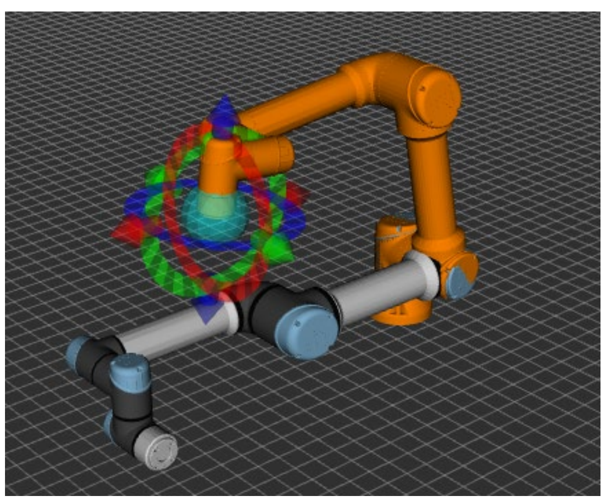

Figure 8. UR5e robot visualized in original colors with planned state in orange and interactive axes for manual placement of goal

5. RESULTS AND ANALYSIS

To handle multiple tasks and priorities efficiently in robotics, finite state machines (FSM) are often used. FSM are abstract machines that control the logic of a robot using states and transitions. For this project, the UR5e robot could be in the initial mapping state and would only transition to the next state if completed successfully, otherwise it would transition to a fail state. After mapping, the robot waited for human input on where to perform the scooping action. Once provided, the robot finally scooped, collected a sample, and placed it in the collection jar.

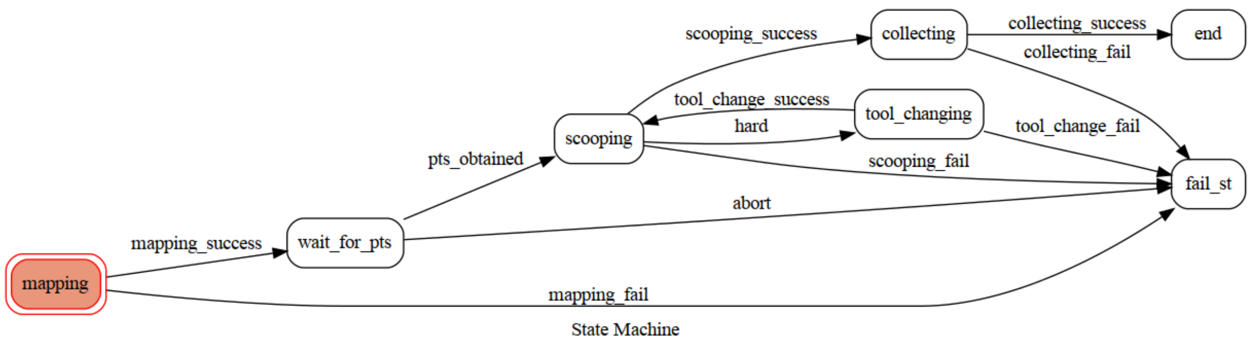

Figure 9. State machine created for off-riser sampling task

Figure 9 shows the state machine created for this application which was created using the Python library "PyTransitions". This library allows state machines to be created and has various additional features for modifying the logic of the system. The figure also shows that the state machine has the extra capability for tool changing, a skill that has not been implemented in the project yet. The FSM however has the state "tool_changing" and the appropriate transitions present as placeholders that as of the writing of this report does not get transitioned to from the scooping state.

The final system that performed the sampling demonstrations is shown in figure 10. This system adjusts the height using the mechanical mounting device. During development, various heights were tested before arriving at the utilized one. The robot was able to successfully perform the scooping of simulant from the test bed with the amount varying from approximately 20-40% of the scoop's capacity. After scooping, the arm collected the sample in a jar mounted above the base and did so with a negligible amount of spilling. Overall, the performance of the robot was robust and achieved the goal it was developed to numerous times.

A concern held before being mounted upside down was the stability and vibration of the total system. If excessive movement of the base occurred, it would negatively impact the system's performance. What was observed were mild movements during activity due to the pallet material being plastic, however, this did not appear to negatively impact the performance of the UR5e when scooping and collecting samples.

An obstacle that appeared during development involved the finding of valid solutions when given a goal in the pose space. The sampling algorithms used for finding a valid trajectory are probabilistic and thus not guaranteed to always find the same solution even if provided with the same goal point. To counter this issue, a wider range for the initial mapping and additional collision objects were implemented. This created more restrictions for the robot's potential trajectory and filtered out nonsensical solutions. Further, some actions which were sent in the Cartesian space were changed to the Joint space where feasible.

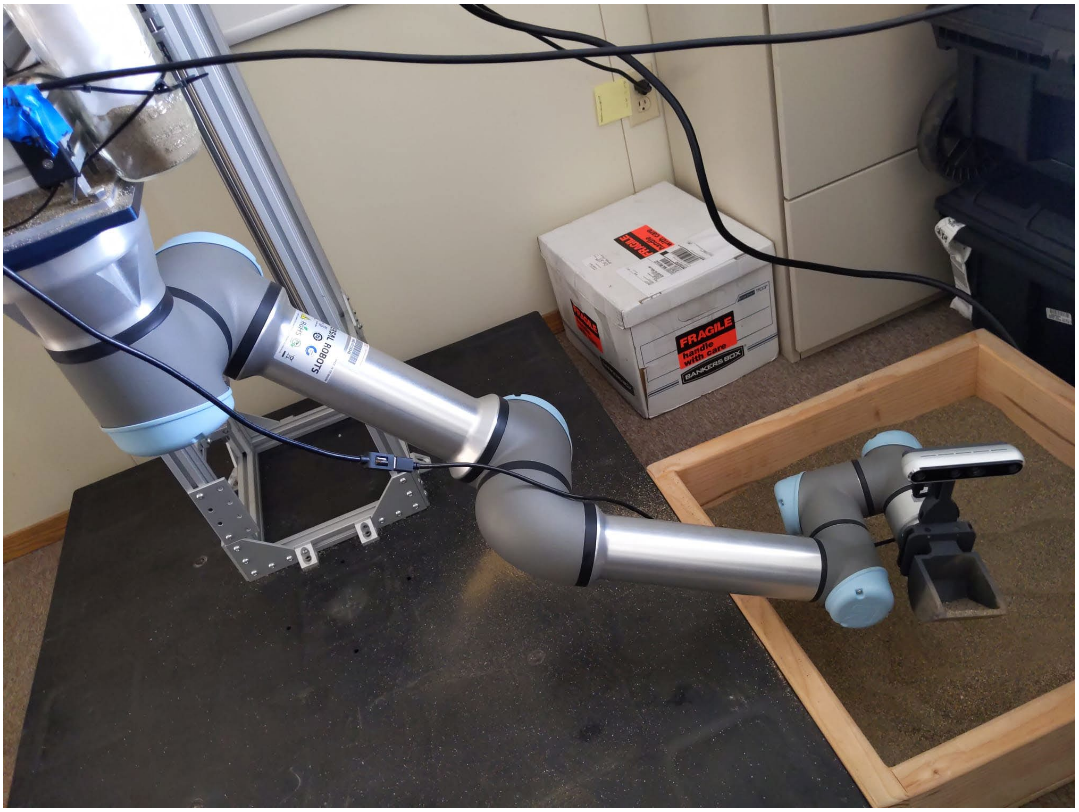

Figure 10. Final setup performing scooping action

A final hurdle worth mentioning is the rare and random cessation of function during activity. Although rare, it was an issue which required the robot to reboot in order to work again. From troubleshooting, it can be deduced that the ROS2 side of software was not the cause as the communications appeared intact when the issue occurred. Thus, the issue was either a bug in the UR5e's pendant, or a safety mechanism, or an issue with the ethernet communication notice of a potential hardware issue.

Some future considerations include testing additional end effectors, increasing the robustness of finding ideal solutions for trajectories, and altering the base mount to match with what would be more realistically expected in a future deployment. The additional end effectors could tackle the issue of the tank sludge being non-homogeneous and thus requiring different techniques for collection. Further, the base of the robot would need to be more loosely suspended which reflects how the robot would be deployed if dropped down a riser. Overall, the task has been successfully demonstrated with the robot manipulator and its corresponding setup.

6. CONCLUSION

A robot manipulator setup was able to successfully demonstrate semi-autonomous off-riser sampling of tank waste for the Chief Technology Office (CTO) at Washington River Protection Solutions (WRPS) to aid in the cleanup mission at Hanford's tank farms. The development of this technology could help aid in the collection of waste via sampling. The UR5e platform from Universal Robots was used in combination with a depth camera from Intel called the RealSense D455 to have a robot platform that can perceive its environment and make intelligent decisions from such data. Software was written to clean the point cloud data, move the robot, and wrap everything together with a state machine while leveraging the Robot Operating System 2. A mechanical mounting system, a passive scoop end effector, and a test bed with simulant were all used to create a demonstration of off-riser sampling using the UR5e robot. The robot was able to repeatedly perform successful demonstrations of its capabilities showcasing the possibility of having autonomous agents collect samples to aid in the Hanford cleanup mission.

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