FLORIDA INTERNATIONAL UNIVERSITY

Miami, Florida

DEVELOPMENT OF A ROBOTIC MANIPULATOR FOR OFF-RISER SAMPLING AT HANFORD SITE~~DEVELOPMENT OF AN OFF-RISER SAMPLER SYSTEM FOR HANFORDS WASTE TANKS~~

Formatted: All caps

A thesis submitted in partial fulfillment of the

requirements for the degree of

MASTER OF SCIENCE

in

MECHANICAL ENGINEERING

by

Philip Moore

2024

To: Dean Ines Triay Melendez PhD.
College of Engineering and Computing

This thesis, written by Philip Moore, and entitled DEVELOPMENT OF AN OFF-RISER SAMPLER SYSTEM FOR HANFORD'S WASTE TANKS, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this thesis and recommend that it be approved.

Benjamin Boesl PhD.

Dwayne McDaniel PhD.

Leonel Lagos PhD., Major Professor

Date of Defense: ~~August~~ October ~~16~~4, 2024

The thesis of Philip Moore is approved.

Dean Ines Triay Melendez PhD.
College of Engineering and Computing

Andres G. Gil
Vice President for Research and Economic Development
and Dean of the University Graduate School

Florida International University, 2024

DEDICATION

To my beautiful wife and loving parents, who's love, support, and encouragement have made this research possible.

To my mentors, who's patience and instruction I have greatly benefited from.

To my fellows, who's mutual respect and understanding is unequalled.

ACKNOWLEDGMENTS

I would like to thank Dr. Leonel Lagos and Dr Ravi Gudavalli for their time and dedication to the DOE Fellows program. I would like to thank my master's committee for their time and patience. I would like to thank my mentors at FIU-ARC: Joseph Sinicrope and Anthony Abrahao. Special thanks to DOE Fellow Theophile Pierre, who has dedicated many hours to this project and will continue it after me. This research was made possible through the funding and support of the DOE-FIU Science and Technology Workforce Development Program sponsored by the U.S. Department of Energy, Office of Environmental Management, under Cooperative Agreement DOE-EM0000598.

ABSTRACT OF THE THESIS

DEVELOPMENT OF AN OFF-RISER SAMPLER SYSTEM FOR HANFORD'S WASTE TANKS

By

Philip Moore

Florida International University, 2024

Miami, Florida

Leonel Lagos, Major Professor

Formatted: Font: Not Bold

Formatted: Line spacing: single

Formatted: Font: Not Bold

develop a pneumatic sampling system to take material samples of the sludge in the bottom of the single shell tanks at Hanford site. This task poses several challenges including the height of the tanks, the small diameter of the risers (four-inch diameter pipes that run from above grade down into the tanks), the high doses of radiation inside the tanks, and the viscosity of the waste. The design is a four degree of freedom manipulator comprising four bespoke pneumatic joint called joint members. This study also addresses the development of a stabilization system to keep the system stable while suspended from cables. Initial testing has been completed, with further refinement of the performance of the joint members planned.

~~CHAPTER~~ PAGE

TABLE OF CONTENTS

~~CHAPTER~~ PAGE

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

~~CHAPTER~~ PAGE

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

Formatted ...

~~CHAPTER~~ PAGE

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

Formatted: Default Paragraph Font, Check spelling and grammar

~~CHAPTER~~ PAGE

LIST OF TABLES

TABLE

~~CHAPTER~~ PAGE

LIST OF FIGURES

~~CHAPTER~~ PAGE

~~CHAPTER~~ PAGE

CHAPTER 1

INTRODUCTION

1.1 Background

In 1977, the newly formed United States Department of Energy (DOE) replaced the dozens of committees and commissions that previously regulated nuclear technology, including the Atomic Energy Commission [1]. The DOE Office of Environmental Management (EM) is responsible for managing the legacy sites that produced the components for nuclear weapons and responsible for keeping their impact on the environment and the US public as low as reasonably achievable (ALARA). One of the largest and most challenging of these sites was Hanford [2].

The Hanford Nuclear Site was established in 1943 and played a crucial part in national and world history by producing plutonium for the Manhattan Project and throughout the Cold War [2]. Today, Hanford takes up approximately 580 square miles of desert in the southeast of Washington. While Hanford no longer produces plutonium, the site is now one of the world's largest environmental clean-up projects including approximately 56 million gallons of waste [3]. In 1944, Hanford began construction on the first of 149 single-shell tanks (SSTs) to store the high-level waste produced during the research, development, and production of weapons grade plutonium [3]. These SSTs were made of concrete and carbon steel and had an original design life of 20 years. A diagram of an SST can be seen in Figure 1-1. These tanks are located in tank storage areas called tank farms [4].

Starting in the 1950s, two leaks were detected in the SSTs located in the A farm [4, 5] (see Figure 1-2). Since that time 67 SSTs are confirmed or suspected of leaking. These Due to this failure and the approaching end of the SST design life the SSTs were joined by the larger and more secure double shell tanks (DSTs) in the 1960s. These tanks added a secondary shell for additional containment in the event of a leak and had a design life of 50 years [4]. For public and environmental safety, virtually all the liquid waste, also called supernate, was relocated to secure SSTs or DSTs. The sludge waste remains and will eventually need to be stored in a permanent geological repository.

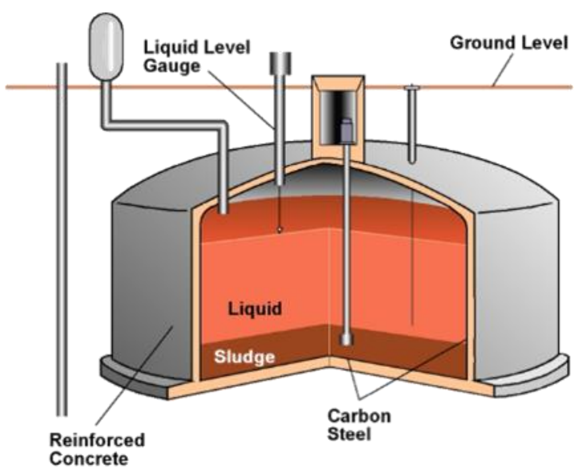

Figure 1-1: Diagram of an SST [4].

As neither the SSTs nor DSTs were planned to be a permanent storage solution to the waste generated at Hanford, both sludge and supernate are eventually planned to be contained in a stable glass form through a process called vitrification. In this process, waste is mixed with silica and placed in high temperature melters. The molten material is placed in steel containers to cool and solidify. Once this glass solidifies, it will no longer have the ability to seep into the soil or groundwater. Low activity waste will be stored underground on site while high level waste will be transported in federal facilities [5]. Unfortunately, the vitrification plant was meant to be operational in 2023 but is still in the test phase [5][6]. Problems remain in the fact that the SSTs have well exceeded their original design life of 20 years and the younger DSTs are quickly approaching their intended design life [4]. However, the sludge waste has not been fully characterized and its exact contents and level of uniformity remain unknown [7]. Sampling and characterization of the remaining sludge waste will prove invaluable to retrieval and closure efforts.

Commented [PM1]: fix

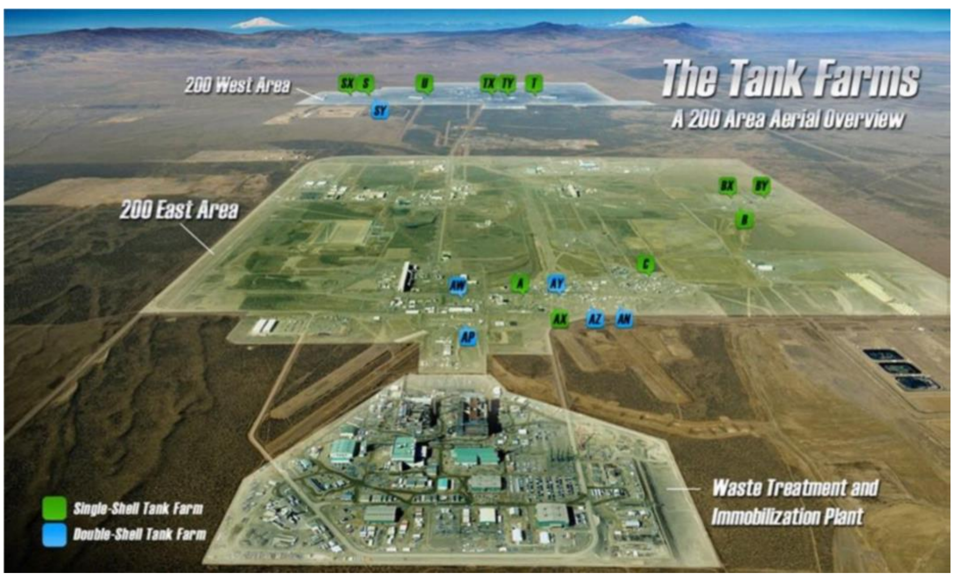

Figure 1-2: Aerial map of the 200 area of Hanford Site [8].

1.2 Motivation

This research has been conducted in collaboration with Washington River Protection Solutions (WRPS), the primary contractor for management of the tank farms at Hanford. WRPS engineers take material samples of this sludge waste to support characterization, retrieval, treatment, and closure efforts. Samples are taken through risers, pipes of varying diameters that start at or above grade and terminate inside the tanks. The smallest of these risers are 4" (inch) in diameter and the largest are 24" in diameter. This task poses several challenges including the height of the tanks, the small diameter of the risers, the highly radioactive environment inside the tanks and viscosity of the waste itself.

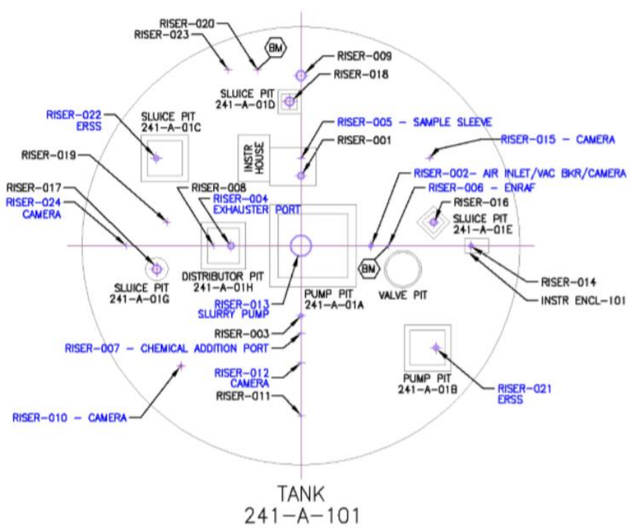

Figure 1-3: Sample SST layout from A farm (tank 241-A-101), including the locations of pits and 24 risers [9].

Currently, samples are taken manually, by lowering a clamshell clamp and triggering it to close around a portion of waste. This method provides WRPS with a limited number of data point, equal to the number of risers available for them to sample from. This method does not provide them with sufficient data to complete chemical and radiological characterization of the waste or determine if the sludge is uniform across a single tank. WRPS has explored sampling alternatives to resolve these issues, however, most proposed solutions required a minimum of two risers and utilized larger risers. These larger risers would be too challenging to utilize because many of them are occupied with permanent equipment that cannot be uninstalled. As part of the DOE-FIU Cooperative Agreement, DOE and WRPS have requested FIU to develop a sampling system using a robotic manipulator, which could deploy from a single four-inch diameter riser and provide a large sampling area once deployed. The potential sampling points that the proposed system would provide can be seen in the risers in Figure 1-3. Development of such a remotely operated sampling system will greatly assist the DOE and its contractor WRPS to meet their safety and retrieval goals by providing information on the knowledge and consistency of waste in evacuated single shell tanks without introducing unnecessary risk.

1.3 Proposed Solution

Of the challenges posed by this research, the most significant is size constraints posed by the four-inch diameter risers. The use of larger diameter risers would allow more leeway in the design, however most of the larger risers are occupied by permanently installed equipment (see Figure 1-3) that is either impossible or too costly to uninstall for the temporary deployment of a sampling tool. This comes with the added benefit that if the system can be deployed from a four-inch riser it can likely be deployed from any larger riser that may be available. These factors lead to three design constraints: The manipulator would need to be no larger than 3.5” in diameter[1] (1), have as long a reach as possible (realistically between ~~3’~~ three~~(foot)~~ and six feet~~6’~~) (2), and would be able to operate in the hazardous tank environments (3). A standard SST from A farm can be seen in Figure 1-3. This includes the risers, which serve as the potential sampling points. Furthermore, Hanford requires that any equipment that contacts the waste must be able to survive 26,200 R/hr of beta radiation and 394 R/hr of gamma radiation [10]. The presence of radiation eliminates the use of many digital sensors that would typically be used in a manipulator such as cameras, optical encoders, and inertial measurement units (IMUs).

If a small profile, relatively high payload sampler in the form of a robotic manipulator were developed, then it would greatly assist WRPS in their task of characterizing the waste stored in evacuated tanks. This would not only benefit WRPS and Hanford, but any industry that would need to inspect or sample from confined spaces or hazardous environments.

[1] The effective diameter is reduced by .5” to account for potential corrosion in the riser. This protects from the device getting lodged when being deployed or retrieved.

enter a radioactive environment, accessed through a four-inch diameter aperture. While this is a complex problem with many components, this research is only concerned with the manipulator and its controls. The method of lowering it into the SST and stabilizing it, so it can collect samples are in the process of being discussed and will require separate research and development (R&D) efforts. This research assumes that the height of the manipulator in the tank can be externally controlled, and the base of the manipulator is fixed once the height has been set.

CHAPTER 2

LITERATURE REVIEW

2.1 Waste Retrieval Systems

Waste retrieval is a problem of recent development and necessity. Before the events of the Manhattan process, the consequences of storing long-lasting fission products with hazardous chemicals in underground tanks was not well understood. Now that the DOE finds itself in that situation there is limited experience, successful or unsuccessful, to draw from. The retrieval systems made to address the problems posed by the Hanford SSTs (as well as the future challenges posed by the DSTs) can be divided into two categories: wet retrieval and dry retrieval. Wet retrieval uses water to mobilize solids in the heel of the tank. Dry retrieval prioritizes adding as little moisture into the tank environment as possible. The reasons to select a dry retrieval system are twofold, firstly because any clean water that enters the tank itself becomes contaminated waste, increasing the volume of contaminated liquids that must be remediated. Secondly, it cannot be used in tanks that leak or are suspected of leaking due to the inherent danger it imposes. The very purpose of the wet system is to cause the stationary sludge to flow more easily. The waste would be as likely to flow out of the leaking liner and into the sediment and groundwater as to flowing towards the retrieval system [11].

2.1.1 Wet Retrieval Systems

While these systems are not directly applicable, these advanced robotic tools had to overcome many of the same challenges that a dry retrieval system must face. The primary form of wet retrieval of sludge waste is a process called sluicing. In this process, pressurized water is blasted at hard or crusted waste, both breaking it up and hydrating it into a slurry. This loose, diluted sludge waste could then be pumped out of the tank. WRPS lessens the impact of a wet sampling system by using recycled tank supernate that is already contaminated as opposed to clean water. Sluicing is used to move large portions of waste; however, it is undesirable for sampling. Firstly, it dilutes the sample and if uniformity of waste is being evaluated, it may mix waste together that would have remained separate if not for the jets of water. It would also dilute the sample by an unknown factor. Sluicing can be used for neither sampling nor large scale retrieval in leaking tanks due to the risk of release [11].

The current sluicer design used by WRPS, implemented circa 2013, places the sluicer cannon on a 3-degree of freedom robotic manipulator to get the water jet closer to the desired location (see Figure 2-1). Deployed from a 12” riser, this system utilizes hydraulics actuators to give up to 30ft of range to the sluicer, a chain drive system to change the elevation of the nozzle and keeps sensitive components in a shielded container above the surface, away from radiation [12].

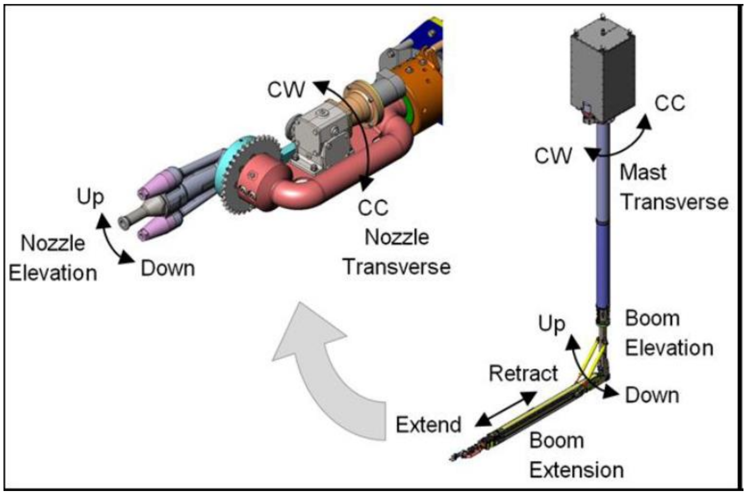

Figure 2-1: WRPS long reach sluicing arm [12].

2.1.2 Dry Retrieval Systems

Dry retrieval systems have been considered for use with the SSTs at least since 1994. During their time managing the tank-farms, former tank farm contractor Westinghouse Hanford Co. suggested replacing the sluicing process with a long-reaching manipulator intended to enter SSTs above an unspecified size threshold. Unfortunately, the details of the Westinghouse sluicing alternative are limited, and the available report avoids information about the mechanisms that power the dry-retrieval system. What is clear is that it uses a long-reach manipulator deployed from the central 42" riser found at the center of most SSTs. The manipulator was supported by a large mast on a bridge, startled over the tank as seen in Figure 2-2 [7].

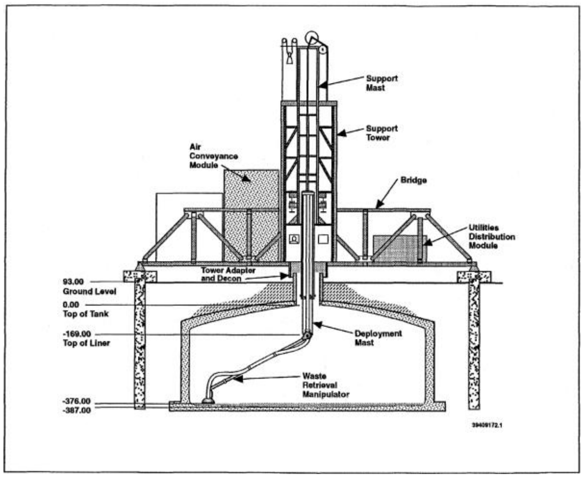

Figure 2-2: Westinghouse dry retrieval manipulator [7]

This manipulator was capable of utilizing “a wide variety of retrieval tools ...”. An air conveyance system would then be used to transport the collected samples to the surface [7]. It is difficult to verify whether this technology was ever utilized by Westinghouse, but it greatly resembles newer retrieval technologies currently in use by WRPS.

in 2023, Savannah River National Laboratory (SRNL) made a report to evaluate technologies for dry retrieval. Herman et al. states that, apart from increasing safety in the SSTs, dry retrieval has the ability to accelerate retrieval efforts and reduce the overall cost of retrieval, noting that reports show that infrastructure upgrades that support the current plans for large scale retrieval are expected to cost approximately ~~$1~~one billion dollars. While the technologies selected for this survey were intended to use of large-scale retrieval or various tasks associated with large scale retrieval, the technologies many be applicable to smaller scale sampling operations. This report focuses on leveraging technologies from other industries that could be repurposed or retooled for retrieval activities with little change to existing infrastructure.

Apart from the system that reaches the surface there is also the end effector that will collect the waste. As previously stated, the use of pressurized fluid would be inadvisable for this purpose, so the methods should be constrained to mechanical in nature. While there is little information on the mechanical methods used by Westinghouse's design, the problem set resembles those posed by a sampling mission to space. Engineers wishing to sample regolith from the Moon or Mars will encounter soil of unknown texture and uniformity. Such a system must be able to adjust rapidly and without user interaction. A jack hammer like tool used to break up tough terrain, could similarly break up dried or hardened sludge waste. Augers could then be used to collect the loose or loosened sludge sample. Figure 2-3 shows different auger configurations to collect regolith samples. Another option is a clamshell claw Figure 2-4. This method can provide only surface samples [13].

The clamshell claw shown by Zhang et al. for regolith sampling closely resembles the method currently used by WRPS but adding it to the end of a manipulator would allow it to sample a much wider area. Each of the aforementioned sampling systems are already being used for other purposes without diluting the samples. A robotic system could utilize multiple end-effectors through a quick-change system.

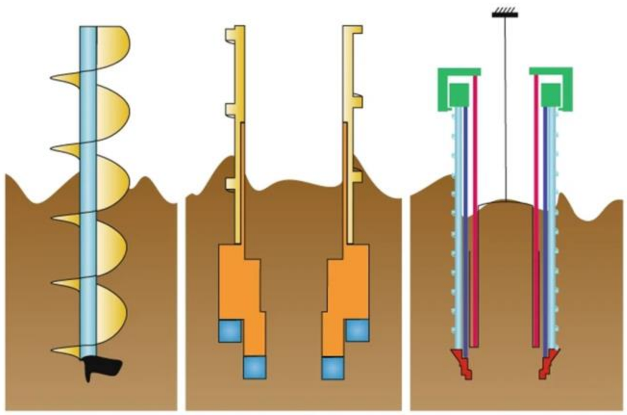

Figure 2-3: Auger configurations [13].

A pneumatic tool change system, like those offered by Schunk or ATI, allows for near instant tool change with pneumatic pass-throughs for the tool itself (Figure 2-5).

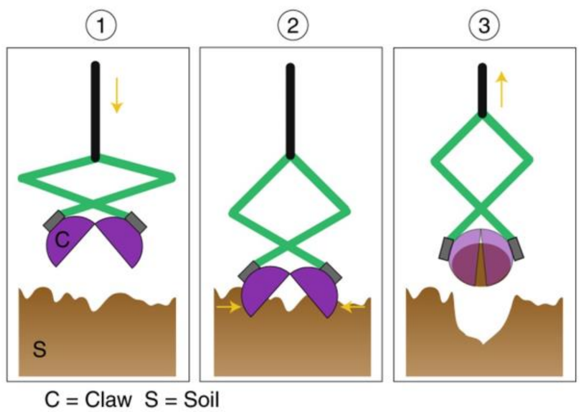

Figure 2-4: Claw design [13].

Figure 2-5: ATI active tool changer (orange) at FIU-ARC: master side (A), tools side with a suction tool installed (B).

2.1.3 Fukushima Fuel Retrieval

Another example of waste retrieval can be found in Japan following the Fukushima Daiichi incident. On March 11th, 2011, a 15-meter tsunami caused by a major earthquake struck Fukushima prefecture. This triggered a meltdown in three reactor cores. This natural disaster caused massive loss of life and damage to millions of buildings. As an area of high seismic activity, all nuclear plants had emergency shutdown procedures for just this purpose. Fukushima Daiichi plant however suffered destruction of its backup generators and the cores of four reactors failed as a result. Units one, three, and four suffered hydrogen explosions that damaged the facilities, further complicating retrieval [14].

Due to the deadly radiation still present in some parts of the facilities, robotics are being used to address several key issues including inspection, repair, and fuel retrieval. The fuel in the facilities was originally in two locations: either in a reactor unit or in a spent fuel pool. The fuel in the waste pools did not move, and while wreckage of the damaged facilities restrict access to them, they are already equipped with tools designed specifically to remove them. Due to the meltdown, the fuel relocated to various parts of the reactor, leading to a more challenging retrieval [15]. While the incident is quite different from the situation at Hanford, it creates many of the same challenges: High radiation, limited access, confined space, development of specific tooling, and uncharacterized waste [16].

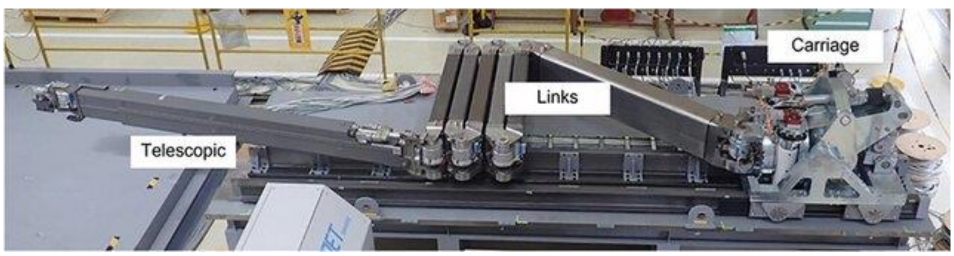

Figure 2-6: Veolia robotic Arm [17].

UK based manufacturer Veolia had manufactured two robotic solutions for use at reactor unit two~~2~~ at Fukushima Daiichi. These systems are called the Fukushima Inspection Manipulator and Fukushima Repair Manipulator (FIM and FRM). Together, they were designed to inspect and repair leaks to prevent further environmental contamination as well as make future retrieval efforts easier. These systems were built on a shared platform that was designed to be installed onto existing hardware at the nuclear site. FIM was deployed in 2014 after rigorous testing and completed its task. FRM arrived in Japan in 2016 and completed its operations from 2017-2018 [16]. Following these successes, Veolia developed a complicated folding robotic arm capable of snaking its way up to 21 meters through the complicated internal structure of reactor two~~2~~ (Figure 2-6). This system is set to be deployed in 2024 [18].

2.2 Robotic Arms

The first robot for material handling was patented in 1954 by George Devol. Devol's partnership with Joseph Engleberg would bring about the first robotic arm, Unimate #001 ~~(Figure 2-7)~~, in 1959, with the patent being awarded to Devol in 1961. The pair would go on to open a company named after that arm, Unimation, and their first customer was vehicle manufacturer General Motors.

Since then, the use of robotics would continue to grow, becoming an everyday part of industry in the early 1980s. Robotic manipulators are used to complete repetitive or hazardous tasks. It is the ability of robots to act where humans cannot that relates to the topic at hand. The environment that this proposed manipulator will be entering is extremely hazardous and poses multiple risks to human life that makes manual work inside the tanks inadvisable, if not, entirely impossible.

Robotic manipulators are categorized by their degrees of freedom (sometimes called axes). A degree of freedom refers to a point of articulation or unrestricted motion. The joints that make up a degree of freedom can be prismatic (one that translates along an axis) or revolute (one that rotates about an axis). Most industrial robotic arms are comprised completely of revolute joints. The reasons for this are twofold. Firstly, every objects position in space with regard to a specific frame of reference can be described using six parameters, three translational, and three angular. While revolute joins can be used to create translation of the end effector, prismatic joints cannot be combined to induce rotation. Therefore, to interact with a point within the robot's workspace from any angle, a robot would need six~~6~~ degrees of freedom, with at least three being revolute joints, with the remaining three~~3~~ being either revolute or prismatic. As most electric motors take in the form of revolute joints, and that these forms are quicker and more maneuverable than their prismatic counterparts, most modern robotic arms are comprised of six~~6~~ revolute joints. Though some manufacturers opt for one or more prismatic joints based on the application.

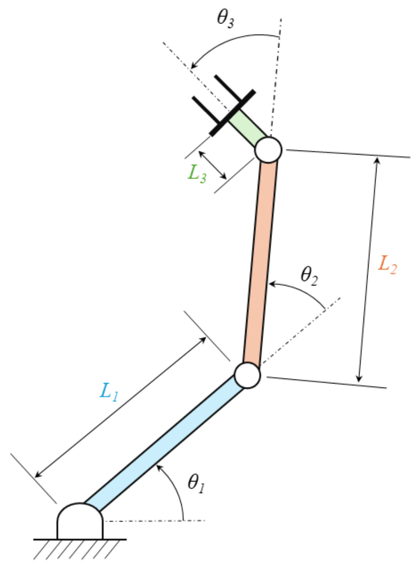

Figure 2-7: degree of freedom planar robotic manipulator [19].

The properties of a robotic manipulator are expressed in a link parameter table, an example of which can be seen below in Table 2-1. This example gives the parameters of a planar, three~~3~~-degree of freedom, robotic Arm, where *i* is the joint, α_{i-1} is the angular offset between joint *i* and joint *i* − 1, a_{i-1} is the distance offset between joint *i* and joint *i* − 1, d_i is the translational motion of the joint and θ_i is the rotation motion of the joint.

Table 2-1: Link parameters of a three-link planar manipulator [19].

i	α_{i-1}	a_{i-1}	d_i	θ
1	0	0	0	θ_1
2	0	L_1	0	θ_2
3	0	L_2	0	θ_3

Formatted: Space After: 0.2 pt

Formatted: Space After: 0.2 pt

Formatted: Space After: 0.2 pt

Formatted: Space After: 0.2 pt

Furthermore, the UR5e was also unlikely to work in the tank on account of the many digital sensors it requires to operate properly. This combined with the physical size of the arm, which well exceeded the confines of the 4” riser meant that while this was a valid proof of concept for the use of robotics for waste sampling, it would never be deployed. FIU has searched for alternative commercially available arms to fulfil this task, but available arm was found that could fit through the 4” riser while providing a suitable reach for sampling. The smallest Universal Robotics arm, the UR3e, has a footprint of about 5” and has a shoulder that is not factored into that measurement, meaning it would not even fit through the larger 6” diameter risers [21].

Figure 2-8: Proof of concept system demonstrated at the WRPS [20].

2.3 Pneumatic Joints

Pneumatic actuators are used for their low cost, high power to weight ratio, versatility, compact size, and inherent safety (as both electric motors and hydraulics heat up under high loads) but these features come with some limitations. Unlike hydraulic joints, the compressible nature of the fluid used makes it more difficult to create precise motion. Most pneumatic joints are intended to exist in two states, opening or closing, with some exceptions such as indexing rotating joints and air motors. For these reason pneumatic joints are mostly used in automation applications where quick, repeated motions are desired. The most prevalent pneumatic joint is the ubiquitous air cylinder. These are linear pneumatic that can be found in a number of configurations such as: single acting, double acting, and low-profile cylinder. Single acting (or spring return) which only requires a single air line but gives limited control over the speed with which it retracts; a double acting cylinder which has two air chambers and two air inputs, granting greater control over the forces and speeds with which the rod extends and retracts. A double rod cylinder can be single or double acting but has two rods, eliminating the ability of the rod to freely rotate. Low-profile cylinders can have any combination of the previously mentioned traits but minimize the length of the cylinder to barely longer than the stroke of the cylinder. These are sometimes referred to as pancake cylinders.

Some research has indicated that more creative pneumatic joints can be constructed that can maintain loads at any desired position in between fully open and fully closed. Rouzbeh et al. investigated precise control methods for a pneumatic rotary joint. Their research sought to address the accuracy and closed loop control issues associated with pneumatics due to the compressibility of air. Their joint utilized pneumatic cylinders that actuate a rack and pinion system (Figure 2-9~~Figure 2-10~~). Their system monitored pressure and position via encoders and modulated pressure to minimize overshoot. Using a model-based pressure control system, their test prototype remains accurate and stable, even under varying load [22].

Similarly, Varseveld et al. proposed a novel control system for a pneumatic cylinder using a discrete on-off system. Both position and velocity of the are measured and used in the control loop. In a method similar to a position integral derivative (PID) control loop, by observing these factors, the system attempts to critically damp the system to ensure the actuator reaching the target quickly while producing minimal oscillation [23]. The novelty of this approach is the use of the discrete on-off solenoid valves with pulse width modulation (PWM). One chamber of the cylinder is held open (at atmospheric pressure) and the other

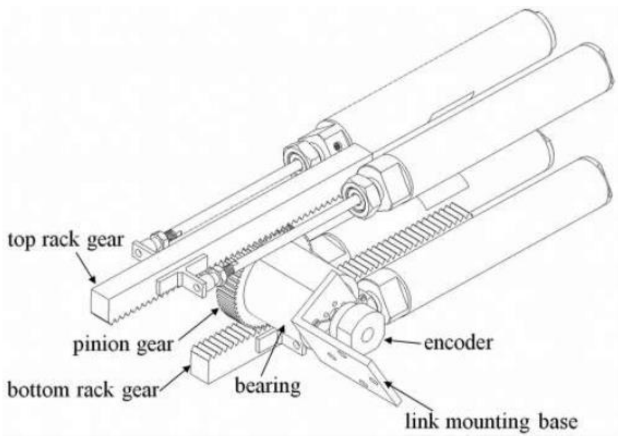

Figure 2-9: System for precise control of a pneumatic manipulator by Rouzbeh et al. [22].

has pressure enter in pulses through the PWM operated solenoid valve. Speed of actuation was controlled using an open control loop. This control loop considered the nonlinearity of the compressible fluid and combined values from analytical modeling with real time position feedback to produce quick and accurate motion. The use of solenoids alone instead of costly servo valves that can precisely control pressure keeps costs low and produce adequate accuracy. This method achieved very small solid-state errors [23].

2.4 Radiation Hardness

A major consideration while selecting materials for designs that will interact with waste inside the Hanford's tank is radiation (rad) hardness and waste compatibility. Radiation hardness is a material property that describes the materials resistance to damage from ionizing radiation such as alpha and gamma radiation. Hanford requires that designs entering the tank environment should be able to withstand 394 R/hr of gamma radiation and 26,200 R/hr of alpha radiation [10]. Metals such as aluminum, steel and stainless steel, and nickel-based alloys all have such high rad hardness that they can remain in a radioactive hot environment indefinitely. However, polymers very greatly in rad hardness and sampling systems must account for how long they are required to operate in the radioactive environment.

Sandia National Lab has conducted research intended to replace the anecdotal evidence used in the past to determine what materials are used in radioactive environments. White et al. characterized the performance of glasses and polymers used in engineering that may be considered for use in a radioactive environment. The area of this research that concerns this paper is the section on polymers. Unfortunately, this paper does not give sufficient information concerning the effect of rad environments towards certain polymers. It provides information on the performance of polymers when exposed to gamma however, for many of the polymers tested the only values given are in a bar graph with a logarithmic scale. However, it provides exact information on polymers that are of great concern to this research including Acrylonitrile-Butadiene-Styrene (ABS) which is a common plastic for 3D-printed and mold injected parts, Polycarbonate (PC) which is commonly found in electronics, and Polytetrafluoroethylene (PTFE) which is commonly used in pneumatic tubing. ABS and PC both preform very well in a high gamma environment. PTFE, however, may have taken a long time to fail, but became brittle at a much lower dose [24]. This would make PTFE a poor material for the intended use of pressurized air lines.

A second consideration is waste compatibility. Some materials, such as aluminum, brass, bronze, and copper are reasonably resistant to radiation but are not considered waste compatible due to potential chemical interaction. This could include simple reactions such as faster than usual corrosion, or as dangerous as thermite reactions [10]. This can both degrade the tool as well as introduce unknown chemical hazards that undermines the work of WRPS and DOE-EM to decrease risk to personnel and the environment. For these reasons any material on the exterior of a tool that will have intentional or incidental contact with should be either stainless steel or one of the materials outlined in the "Standard for the Selection of Non-Metallic Materials in Contact with Tank Waste". This standard outlines the materials that can be used in the in-tank environment with direct or indirect contact to waste assuming an operational life of 5000 hours.

CHAPTER 3

METHODOLOGY

The following sections documents the process of designing and testing a pneumatic manipulator that can enter a radioactive environment, accessed through a 4" aperture. This research is concerned with the manipulator and its controls. The method of lowering it into the SST and stabilizing it so it can take samples are still being discussed and will necessitate their own research and development. This research assumes that the height of the manipulator in the tank can be externally controlled, and the manipulator is rigid in space once the height has been set.

Success of this system is going to be measured in the weight of the final payload, the maximum reach of the arm, adherence to the geometric constraints of the system, ability to work in the hazardous environment, and safety. Of these factors, safety is by far the most important. Under no circumstance should failure of the system result in exposure of the public or environment to radioactive material. Additionally, risk of the system falling into the tank or getting stuck in the riser should be minimized to avoid the need for additional in tank activities to retrieve it, as that poses additional risk.

The desired payload for the arm was set to 10lbs after discussion with WRPS engineers. Samples should weigh no more than 500g, or approximately 1.1lb, but the weight of end-effectors as well as additional force required to do things like physically scoop waste or break up portions of hardened waste. This force will be closely related to the reach as torque is a force over distance. The desired payload must be achieved over the desired distance of between three~~3~~ and six~~6~~ feet that was discussed with WRPS.

3.1 Evaluation of Actuators

The type of actuation is the most important factor for all five of the design criteria. The actuator selected should be able to lift the desired payload, which would require a torque of between 30 and 60 lb ft of torque, fit within the confines of the four-inch riser, resist the radioactive environment and not introduce any unnecessary hazard into the tanks. Three types of actuators were considered for their ability to meet these criteria: electric, pneumatic, and hydraulic. Electric motors were the least favorable due to their form factor and low torque at this scale. Any motor with a small enough form factor would not supply enough torque to scoop a sample of the sludge waste, which is said to have the consistency of wet beach sand (though it is known that the waste has hardened in places) [25]. Also, electric motors pose a spark risk, meaning that they have chance of introducing a spark to potentially flammable off-gassing from the waste. Either hydraulics or pneumatics would work for this application.

Hydraulics were considered for their rigidity, smooth motion, and high loads. Ultimately, pneumatics were selected due to ease of use and low cost for development pneumatics also provide an additional safety feature: as they will be run completely on positive pressure, if a line were to come loose in the tank environment, it would not be transported to the surface. Overall, pneumatic actuation helps to avoid the stricter requirements that Hanford places on hydraulics that enter the tank environment. Like all components that may end up in contact with the waste, the hydraulic fluid must be considered waste compatible, especially since it would be nearly impossible to retrieve if it were to be released. If hydraulics are selected for a future iteration of the design, the fluid used in the final design will be further evaluated.

3.2 Conceptual Design

There already exist a wide variety of commercially available pneumatic rotary joints, however these are mostly made with the automation industry in mind and are ill suited to the use of a robot. Vanes and rotary tables have a limited range of motion and are very weak at the scale that a 4” riser would allow. Instead, this design is based around utilizing the force of a prismatic air cylinder and converting its motion into a revolute joint. Rouzbeh et al. [22] accomplished this using a rack and pinion system which has a very efficient transfer of power. This new design however utilizes a chain drive system. This allows a large cylinder to be used and concealed along the length of the member. A larger sprocket can be used than the pinion could have, giving more mechanical advantage to the system. These members that contain the joint actuators will henceforth be referred to as joint members. The maximum payload and range of motion are determined by the size of the air cylinder and radius of the sprocket.

As previously discussed, most industrial robotic arms have six axes, as this gives them full maneuverability within their defined workspace. This device, however, will not require full maneuverability within that workspace as it is never intended to interact with any surface other than the sludge waste. The act of scooping, drilling or jackhammering can all be easily achieved with only four degrees of freedom. For these reasons, the system was decided to be a four degree of freedom system. Additional axes of motion can be added to tooling or in future iterations if the scope of the project is broadened in the future. Figure 3-1 is an illustration of the four-axis arm's work envelop with its current constraints and dimensions.

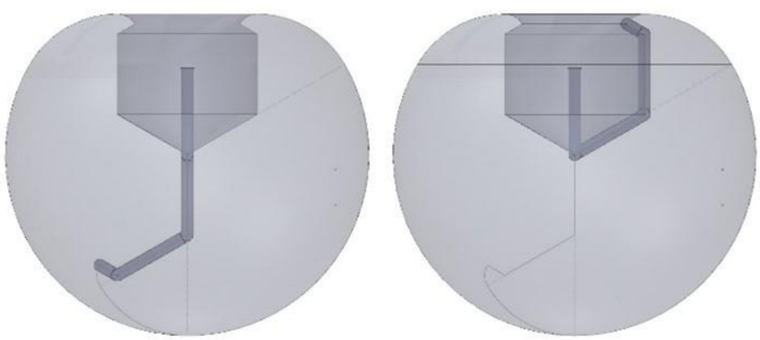

Figure 3-1: Workspace for the proposed system.

3.2.1 Calculations

After the conceptual design was established, specific data was needed to select components such as the air cylinders and the sprockets. The transition of linear to rotational motion means that design changes may inversely affect payload and range of motion. A python script was created in Python Spyder that allowed specific factors to be changed to see how the payload and range of motion were affected. This code accepted inputs on geometry of the components and operational pressure and output the minimum footprint, maximum travel (in degrees), and maximum payload of the joint. The sprocket was confined to the ANSI 35 as it is the lightest chain that could maintain the expected tension.

The most critical physics concept for the development of this system is the force/torque relationship. This law states that an exerted torque is equal to the perpendicular component of the force multiplied by the normal distance. This can be mathematically expressed as:

$$\tau = Fr\sin\theta \tag{3.1}$$

Where τ is the torque exerted by a certain force, F, over a perpendicular distance r. This equation will be balanced at the axes of rotation as the payload exerts a torque over a very long payload. A much more significant force must then be applied by the air cylinder over the much shorter distance of the sprockets pitch radius. The chain drive ensures that the force of the cylinder is always applied perpendicularly to the axis of rotation.

$$F_{cylinder} = P\,\frac{D_{bore}^{2}\pi}{4} \tag{3.2}$$

$$\tau_{joint} = PR_{sprocket}\frac{D_{bore}^2\pi}{4} \quad (3.3)$$

Where $F_{cylinder}$ is the force output of the cylinder, P is the air pressure, D_{bore} is the bore diameter of the cylinder and $R_{sprocket}$ is the pitch radius of the sprocket.

$$\Delta\tau = \tau_{clinder} - \tau_{payload} \quad (3.4)$$

$$\Delta\tau = PR_{sprocket}\frac{D_{bore}^2\pi}{4} - \tau_{payload} \quad (3.5)$$

The torque of any joint n can be determined by the following equation:

$$\tau_{\,n} = F_{load} * \sum_{i=1}^{N} l_i - \sum_{j=1}^{n} l_j \quad (3.6)$$

Where n is the number of the joint, N is the total number of members and l is the length of the member. Therefore, the torque exerted by each of the joints would be:

$$\tau_1 = F_{load} * (l_2 + l_3 + l_4) \quad (3.7)$$

$$\tau_2 = F_{load} * (l_3 + l_4) \quad (3.8)$$

$$\tau_3 = F_{load} * (l_4) \quad (3.9)$$

Similarly, the effect of the weight of the joints themselves can be expressed as:

$$\tau_{weight\,1} = W_4(l_2 + l_3 + l_{CG4}) + W_3(l_2 + l_{CG3}) + W_2(l_{CG2}) \quad (3.10)$$

$$\tau_{weight\,2} = W_4(l_3 + l_{CG4}) + W_3(l_{CG3}) \quad (3.11)$$

$$\tau_{weight\,3} = W_4(l_{CG4}) \quad (3.12)$$

$$F_i = \frac{\tau_i - \tau_{weight\,i}}{l_{lever\,arm\,i}} \quad (3.13)$$

The specifications of each joint in the three degree of freedom prototype can be seen in Table 3-1. Pressure was limited to 120 psi as that was a limitation of the testing apparatus.

However, the maximum pressure that the solenoid valves can utilize is 145 psi.

Table 3-1: Potential payload of system running on 120 psi.

Member	Pressure (psi)	Cylinder Bore dia. (in)	Length (in)	Lever Arm (in)	Weight of Joint (lbs)	Distance of CG	Torque of Joint (in lbs)	Torque due to Weight (in lbs)	Potential Payload (lbs)
Joint 1	120	2.5	23.9	53.8	10.03	10.75	878.91	-	7.54
Joint 2	120	2	23.9	29.9	9.72	12.75	562.50	473.24	13.78
Joint 3	120	1.25	23.9	6	8.32	12.75	132.92	150.47	26.33
End* Effector	-	-	6	-	1.65	3	-	4.95	-

While Joints two~~2~~ and three~~3~~ both exceeded the required payload at the end effector, Joint one~~1~~ was under powered and over encumbered (Table 3-1). The simplest solution was to raise the pressure in that joint to the limit of the system of 145 psi. This could be achieved easily in the field with a portable compressor.

Table 3-2: Revised payloads with increased pressure.

Member	Pressure (psi)	Cylinder Bore dia. (in)	Length (in)	Lever Arm (in)	Weight of Joint (lbs)	Distance of CG	Torque of Joint (in lbs)	Torque due to Weight (in lbs)	Potential Payload (lbs)
Joint 1	145	2.5	23.9	53.8	10.03	10.75	1062.01	-	10.94
Joint 2	120	2	23.9	29.9	9.72	12.75	562.50	473.24	13.78
Joint 3	120	1.25	23.9	6	8.32	12.75	132.92	150.47	26.33
End* Effector	-	-	6	-	1.65	3	-	4.95	-

As shown in Table 3-2, the solution brought the total payload to 10.94lbs which exceeds the nominal payload of 10lbs. However, replacement of plastic parts with metal ones which will raise the weight of the joints, and lower maximum payload. Careful management of the weight of the subsequent joints will need to be removed to reduce the torque they will exert on the first joint. Potential solutions to this will be covered in section 5.2.1.

3.2.2 Joint-Member

This design reached maturity as the joint core design Figure 3-2. The joint core design is modular comprised of the driving end, motion carriage, the idler end, and the actuator core. Modularity was necessary to assist the design and alteration of future joints.

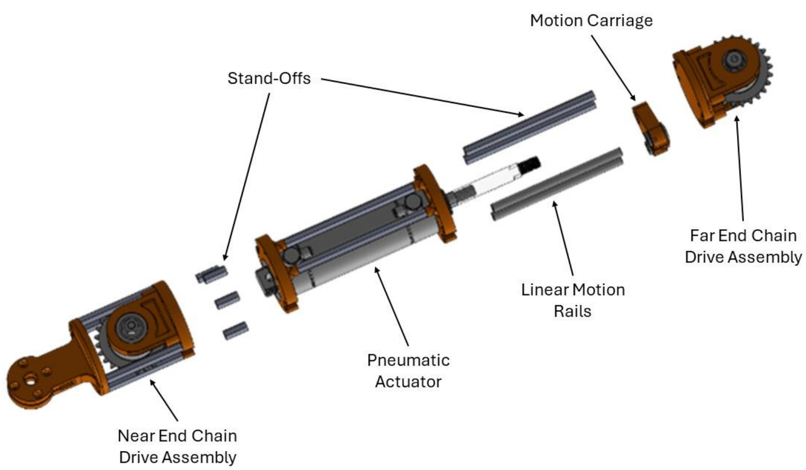

Figure 3-2: Exploded view of a joint member.

As seen in Figure 3-2, much of the strength and rigidity of the design comes from the use of aluminum stand-offs and the steel linear motion rails. The parts that are depicted in orange are 3D-printed ABS plastic. In future iterations some key pieces, namely the linear motion carriage, could benefit from being machined in aluminum in future iterations. Starting from the far end of the joint, the driving end chain drive assembly (Figure 3-2) utilizes a flat American National Standards Institute (ANSI) 35 roller-chain sprocket. The sprocket is connected to the next joint by a four-bolt hole pattern.

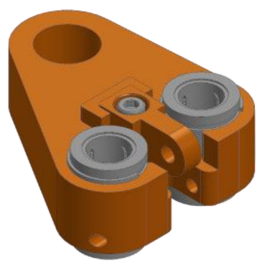

Figure 3-3: Linear motion carriage.

A linear motion carriage (Figure 3-3) was made to transfer the motion of the air cylinder to the chain and is supported by two linear rods. These rods resist the bending moment that the chain and cylinder would exert on the carriage and ensure that the motion is smooth. They also serve as structural members for the design. The original design of the carriage also contained an integrated chain tensioner to ensure smooth operation. This proved to brittle in testing and was abandoned.

Figure 3-4: Actuator Assembly.

The actuator core assembly (Figure 3-4) is designed to use the air cylinder as a structural member to reduce weight and save space. Smaller actuators are used in joints closer to the end effector to reduce weight and therefore torque exerted on the previous joints.

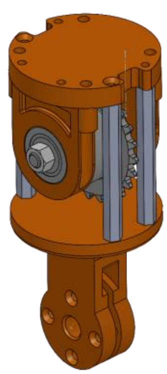

Figure 3-5: Chain drive assembly.

The idler end would be the ideal place to place an encoder to enable precise position control like those used by Rouzbeh et. al. [22] and Varseveld et. al [23]. Originally magnetic encoders were selected to be coupled to the idler sprocket by a pulley. however, they have since been replaced by linear potentiometers as they produce less signal noise and are easier to implement into the controls. Neither of these have been implemented due to continued doubt as to their resilience to gamma radiation and continued development of the controls. If radiation proves to be a limiting factor, then the encoder may be able to be shielded by a material that reflects gamma radiation such as lead.

3.3 Controls

The control system is divided into two boxes, Pneumatic and electrical. The pneumatic box (Figure 3-6) of the system contains three-position, five-way solenoid valves. Unlike the more common two-position solenoid these valves allow the cylinder to be opening, closing, or locked. The operating pressure for this system is 145 psi, but this has been limited to 120 psi during testing due to laboratory limitations. The electronic box (Figure 3-7) is controlled by a microcontroller. This microcontroller sends signals to a solid-state relay board. The solid-state relays toggle on and off the current that runs to each solenoid in the pneumatic box.

Figure 3-6: Pneumatic control box.

Figure 3-7: Electronics control box.

The experimental system is controlled with two joysticks with a single direction corresponding to a degree of freedom. When the user signals that a joint should move, the microcontroller sends a signal for the solenoid to open. If the direction of the input changes, then the solenoid switches from one position to the other and the corresponding transducer. If at any point the input ceases, then the solenoid closes without allowing the pressure to escape. This locks the cylinder right where it is with minimal travel after the input has been removed.

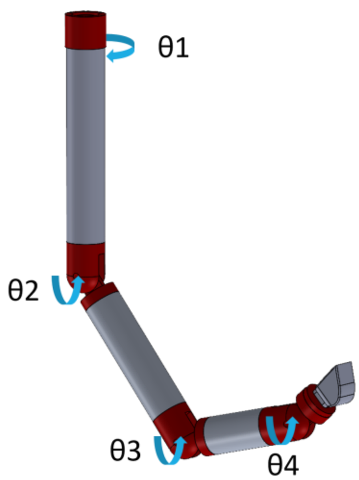

Figure 3-8: Parameters of the four-axis system.

Table 3-3: Link Parameters of a completed four degree of freedom manipulator.

i	α_{i-1}	a_{i-1}	d_i	θ
1	0	0	0	θ_1
2	-90°	0	0	θ_2
3	0	L_2	0	θ_3
4	0	L_3	0	θ_4

Table 3-4: Link parameters of the current three degree of freedom manipulator.

i	α_{i-1}	a_{i-1}	d_i	θ
1	-90°	0	0	θ_2
2	0	L_2	0	θ_3
3	0	L_3	0	θ_4

3.4 Environmental Hazards

The Hanford waste tanks pose some of the most challenging hazards that a robot can be subjected to. Not only will the system be entering a highly radioactive environment with ionizing radiation from decades of nuclear waste, but the humidity can reach 100% with temperatures of up to 200°F, and the pH of the tank can exceed 10 [10]. Certain materials and technologies are susceptible to damage from radiation. Hanford specifies that any waste exposed components must be able rated to 26,200 R/hr of beta radiation and 394 R/hr of gamma radiation [10]. Many polymers become brittle in high Gamma, or even UV. Some common digital sensors that would typically be used in a manipulator such as cameras, optical encoders, and inertial measurement units (IMUs) also fail in gamma rich environments.

Formatted: Font: 12 pt, Not Bold

Formatted: Font: 12 pt, Not Bold

For these reasons, electronics entering the tank will be kept to a minimum. While microcontrollers and solenoids can easily be protected by keeping them above ground, the issue lies in the sensors. The tanks contain multiple, rad hard overhead cameras that could be used to monitor and operate the system, precise control of the pneumatic cylinders requires precise position feedback. This would typically be addressed by optical encoders, but they are known to fail under highly radioactive conditions. Analog encoders and linear potentiometers were considered for this position feedback as they are more radiation resistant than optical encoders. Linear potentiometers were selected as the most direct feedback on the performance of the air cylinder. However, many of these contain components made of unspecified which could degrade over long exposure and give inaccurate readings. This means that performance in the tank environment and exact operational life cannot be determined until more research into the radiation resistance of these sensors is conducted.

Soft polymer tubing is commonly used in the industry to supply pneumatics with pressurized air. Currently, the system uses Polytetrafluoroethylene (PTFE) tubing. While temperature resistant up to 300°F, Hanford found PTFE to be rad hard to about $1.5*10^4$ Rad and may be lesser if under pressure. While less temperature resistant at 176°F, ethylene propylene diene terpolymer (EPDM) is fully rad hard, chemically resistant, and accessible [26]. Results published by Sandia National Lab found that some common thermoplastics such as Acrylonitrile Butadiene Styrene (ABS) performed well in a gamma rich environment with no change in tensile strength up to $5*10^6$ rad [24]. This yields an operation life of 12,690hrs or just under 1.5yrs. However, ABS is not recognized as a waste compatible nonmetallic substance and therefore is not permitted in the tanks. Since aluminum is reactive and therefore not waste compatible, all ABS parts will likely need to be replaced with 316 stainless steel. This will require additional work to reduce the weight of the new machined parts. Methods to do this are covered in 5.2.1.

TESTING AND RESULTS

Testing was performed on the joint-member to ensure that the parts could withstand the torque they would experience if the arm were carrying its maximum payload with a factor of safety of 1.2. After the design for the first joint was completed and again after each design revision, it was tested with an equivalent payload. An equivalent payload is a payload that will produce an equivalent torque on the joint at a different distance from the axis of rotation using the torque relation in equation 3.1. Since the final arm is designed to have a payload of 10lbs with safety of factor of 1.2, at its maximum loading condition the first joint must lift 12lbs at a distance of 52”. Therefore, an equivalent torque can be produced by placing a 40lb weight with a lever arm of 15.6”. This was accomplished with a special, end of arm tool devised to hold a weight that could be increased throughout testing (Figure 4-1).

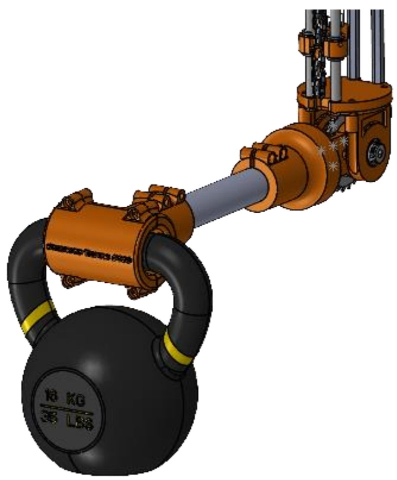

Figure 4-1: Weighted one degree of freedom tester design.

Figure 4-2: Weighted tester on the test mount.

This tester quickly found flaws in the linear motion carriage, which had was too weak when produced in plastic and the design was ill suited for machining in metal (Figure 4-3 [Left]). It failed at a payload of only 10lbs. It went through a series of redesigns that simplified it. The second design (Figure 4-3 [Right]) used metal and 3D-printed plastic but failed after repeatedly lifting 35lbs. This design attempted to use the geometry of the metal part to tension the chain, but this was unsuccessful, as it could not be adjusted.

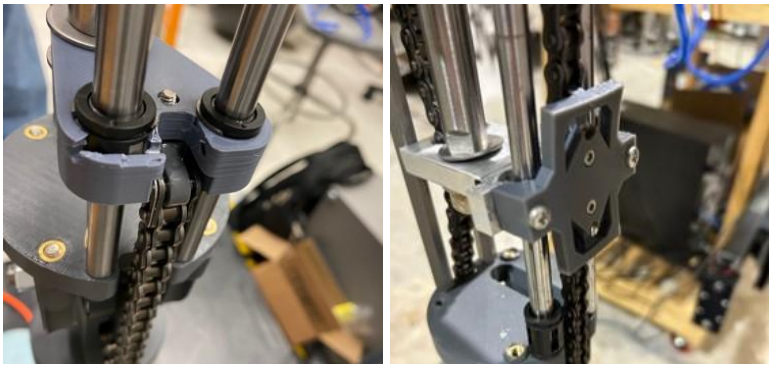

Figure 4-3: Revisions of the linear motion carriage.

The final iteration was a much simpler one. It no longer included a tensioner but was comprised of machined aluminum and a piece of wear resistant hardened steel to hold the chain. After this iteration, the arm was able to withstand 45lbs at a distance of 15.6” but as unable to lift it fully due to the development of a kink in the chain due to the lack of a tensioner. This showed that while the actuator needs further refinement, the compressibility of the fluid was not an issue.

Figure 4-4: Final machined linear motion carriage.

This led to revisions such as the inclusion a turnbuckle as a tensioner placed in line with the chain. After these changes, the three degree of freedom prototype (Figure 4-5) was constructed and placed on a test mount. The test mount is an aluminum extrusion cantilever design. The cantilever runs on linear rails and has an electric winch which allows the arm to be raised and lowered for testing. The test mount simulates how the arm would behave in the tank assuming a semi-rigid base.

Table 4-1: Tests Conducted

Test Results			
Test	Maximum load (lbs)	Pass/ Fail	Observation
First Prototype	7	Fail	The point of failure was motion carriage. Specifically, the pin that connected the chain to the main body of the carriage was torn out (see Figure 4-3~~Figure 4-3~~ [left]). The screw connecting the tensioner also bent beyond the point of usability.
Revised Resin Motion Carriage	28	Fail	The connecting points for the chain failed.
Aluminum-Resin Motion Carriage	45	Fail	While the design supported the desired load it was incapable of lifting it fully to the maximum angle and experienced visible strain (see Figure 4-3~~Figure 4-3~~ [right]).
Turnbuckle Tensioner	45	Pass	Added an easy way to tension the chain without reducing the strength of the system.
Aluminum and Steel Motion Carriage	45	Pass	This fully machined design combines the light weight of aluminum with a piece of machined tool steel to withstand repeated wear from the chain.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

The system originally used only on-off solenoid valves, but this resulted in sudden and uncontrollable movements. This is likely due to the inconsistent loading as the position of the center of gravity and payload in relation to the joints is in constant motion. This can be addressed by more advanced controls. Finer control of the rate of speed of the solenoid valves can be achieved by introducing a pressure transducer which can ramp pressure up and down for smoother motions or PWM control as proposed by Varseveld et al. [23].

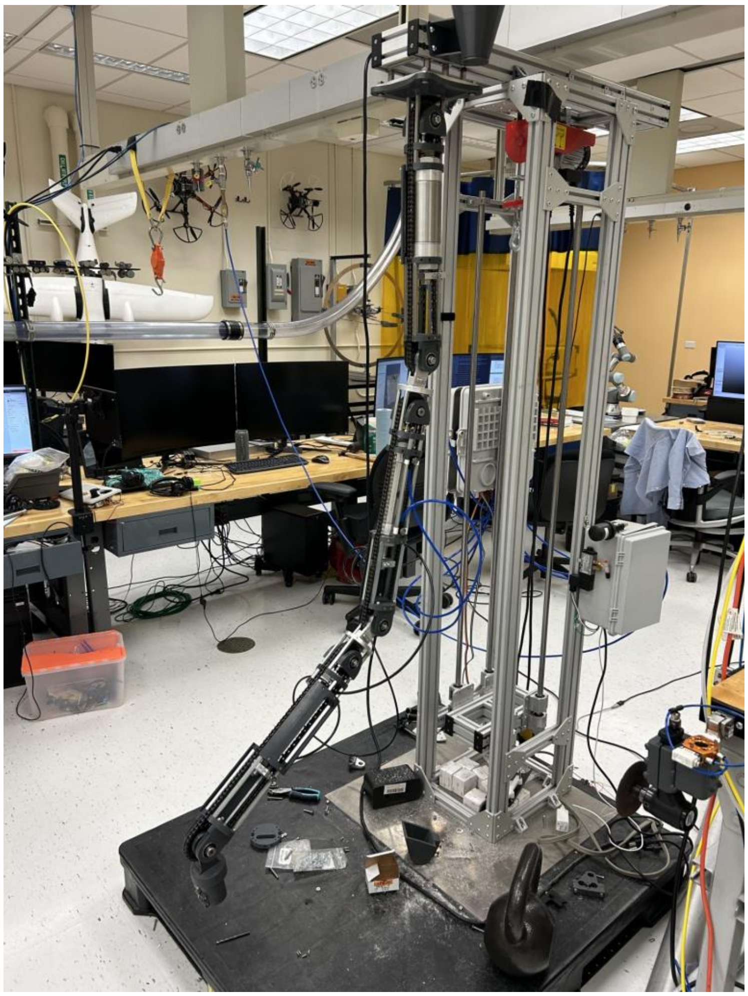

Figure 4-5: Completed ~~3~~ three degree of freedom prototype.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

To conclude, at the time of publishing, the joints has been assembled and are independently capable of lifting the desired load. A three degree of freedom prototype was constructed and a temporary control system for testing was implemented. However, the movement of the joints was jerky due to the on/off nature of the solenoid valves. The introduction of radiation resistant linear potentiometers to create a digital control loop could greatly improve accuracy and ease of use for the operator. It could also pave the way for a semi-autonomous control system. The following recommendations based on the finding of this research could assist in future development of this design.

5.2 Recommendations

The following recommendations could improve future iterations of the robot and address encountered during the development of this research topic.

5.2.1 Radiation Hardness

As this research continues, it will be necessary to continue to modify joints to ensure rad hardness and waste compatibility. This will entail designing light weight stainless steel or aluminum. Aluminum would be confined to parts that are not likely to have even incidental contact with the waste. This area can be expanded by sleeving the arm in a thin stainless steel casing. Lightweight parts can be achieved through a design process informed by topology optimization. According to Rosinah et al., “Topology optimization is a mathematical method which spatially optimizes the distribution of material within a defined domain” [27]. Topology optimization is usually carried out through a computer assisted design (CAD) software. The products are difficult to machine, so unless additive manufacturing is being employed, it is necessary to take the feedback from topology optimization and use it to generate an informed redesign as seen in Figure 5-1.

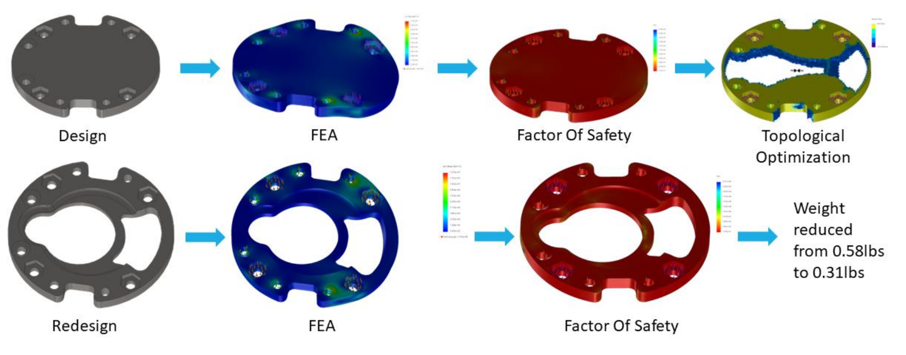

Figure 5-1: Topology Optimization design workflow.

radiation hardening will also entail testing the radiation resistance of sensors that may improve the control side of the system such as potentiometers. The pneumatic tubing currently in use will also likely need to be replaced, either with hard lines (where possible) or with EPDM.

5.3 Future works

This section will address those changes to the design or continued research that are planned or already underway, but not completed as part of this thesis. Once the joints are rad hard and in their final design, we mill move from the planar, three degree of freedom prototype to a four degree of freedom system that can rotate 360 degrees. This will entail designing a base rotational joint that utilizes the same mechanism as the other joints but redirects the rotation 90 degrees. Construct the four degree of freedom system. Once the four degree of freedom prototype is finished, the control systems will need revision to have position control. This will necessitate the use of a rad hard position sensor that has not been identified at this time.

5.3.1 Controls

Considering the shaky movement that plagued the three degree of freedom prototype, new controls will be necessary. As previously discussed, there are two ways this can be achieved: through pressure control or trough PWM. A one degree of freedom test assembly was constructed to test which would be more advantageous before implementing it on the three degree of freedom prototype. A linear potentiometer will provide the feedback necessary to make an open control loop. As an electronic component, the potentiometer will also need to undergo testing to find its operational life in a high gamma environment. This test system will be used to evaluate both control methods for response time, acceleration/deceleration and steady state error.

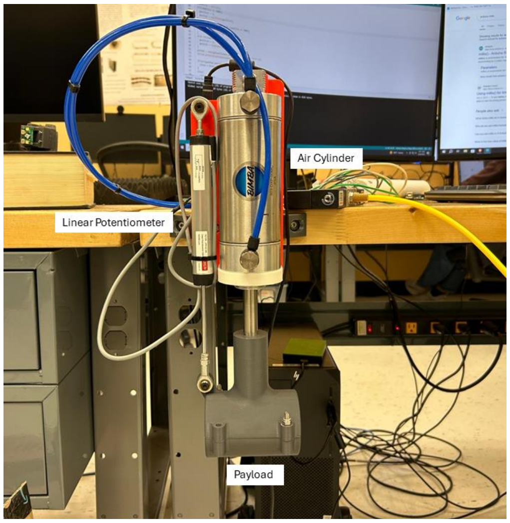

Figure 5-2: One degree of freedom test assembly.

5.3.2 Three Degree of Freedom Cold Testing

This summer, this research was demonstrated at the WRPS Cold Test Facility (CTF) at Hanford by an FIU DOE Fellow summer intern. This student arrived at Hanford in May and brought the system to receive feedback from WRPS engineers, improve upon the design. Throughout this process, WRPS Chief Technology Office will be providing feedback on its performance so that the design can be improved to match their strict standards.

The goal of this internship above all else was to develop end of arm tooling in accordance with the needs of WRPS. Currently, tools must be switched manually by the operator; this process will soon be replaced by an automatic tool changer, as discussed in section 2.1.2. This system will need to go through at least one round of cold testing (testing in a simulated environment with no radiation sources). Following cold testing, the design will then need to undergo a hot test in which it will have to withstand the real tank environment. If it can so this, then it has a potential of being adopted by WRPS for field work.

Figure 5-3: Three degree of freedom prototype at WRPS CTF.

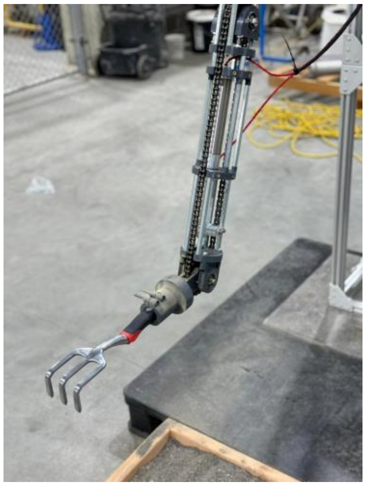

Figure 5-4: Prototyping end effectors at WRPS CTF.

BIBLIOGRAPHY

1. *A Brief History of the Department of Energy*. [cited 2024 05/22/2024]; Available from: https://www.energy.gov/lm/brief-history-department-energy.
2. Gephart, R.E. and R.E. Lundgren, *Hanford Tank Clean up: A guide to understanding the Technical Issues*. Pacific Northwest National Lab.
3. Hatchell, B.K., et al., *Alternate Retrieval A-105 Application Assessment Report.* OSTI, 2016.
4. Gephart, R.E., *A Short History of Hanford Waste Generation, Storage, and Release*. 2023, Washington River Protection Solutions.
5. *Hanford Waste Treatment Plant*. [cited 2023 11/03/2023]; Available from: https://ecology.wa.gov/waste-toxics/nuclear-waste/hanford-cleanup/tank-waste-management/tank-waste-treatment.
6. *Vit Plant Pours First Glass From Second Melter*. 2024 [cited 2024 05/22/2024]; Available from: https://www.hanfordvitplant.com/newsroom/vit-plant-pours-first-glass-from-second-melter/.
7. P. W., G. and M. L B., *First Generation Long-Reach Manipulator for Retrieval of Waste from Hanford Single-Shell Tanks*. 1994, Westinghouse Hanford Company.
8. *The Tanks*. [cited 2024 04/30/2024]; Available from: https://wrpstoc.com/tank-operations/the-tanks/.
9. Henderson, C., *Waste Management Area A-AX Closure Specification*. 2020, Washington River Protection Solutions.

10. Natividad, J.R., *Specification for the Dry Waste Retrieval System (A, SX, & U SSTs)*. 2022, Washington River Protection Solutions.
11. Herman, D.T., et al., *Evaluation of Technology for Dry Retrieval of Tank Waste*, in *OSTI*. 2023, Savannah River National Laboratory.
12. Bauer, R.E., R.R. Figley, and A.G. Innes, *Development and Deployment of the Extended Reach Sluicing System (ERSS) for Retrieval of Hanford Single Shell Tank Waste. Draft.* OSTI, 2013.
13. Zhang, T., et al., *The progress of extraterrestrial regolith-sampling robots.* Nature Astronomy, 2019. **3**(6): p. 487-497.
14. *SAFETY AND SECURITY: Fukushima Daiichi Accident*. 04/29/2024 [cited 2024 07/30/2024]; Available from: https://world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-daiichi-accident.
15. *The Status of Fuel Debris Retrieval*. [cited 2024 07/30/2024]; Available from: https://www.tepco.co.jp/en/hd/decommission/progress/retrieval/index-e.html.
16. *Go Where No Human Can With Innovative Robotic Solutions*. [cited 2024 07/30/2024]; Available from: https://www.nuclearsolutions.veolia.com/en/our-expertise/case-studies/fukushima-daiichi-japan/go-where-no-human-can-innovative-robotic.
17. Wang, Z., et al., *Dataset creation and selection methods with a wire drive flexible manipulator for vision-based reconstruction.* ROBOMECH Journal, 2023. **10**.
18. *Veolia selects Siteflow for Fukushima decommissioning support*, in *World Nuclear News*. 2023: London, UK.
19. Craig, J.J., *Introduction to Robotics: Mechanics and Controls*. Fourth ed. 2019, Hoboken, NY Pearson.
20. Adams, J., *Development of Semi-Autonomous Robotic Manipulator for Off-Riser Sampling of Tank Waste*. 2022, Florida International University Applied Research Center.
21. *UR3E Ultra-Lightweight, Compact Cobot*. [cited 2023 07/17/2023]; Available from: www.universal-robots.com/products/ur3-robot/?utm_source=Google&utm_medium=cpc&utm_cja=Demo&utm_leadsource=Paid+Search&utm_campaign=HQ_US_Always-On2021&utm_content=textad&utm_term=ur3&gclid=EAIaIQobChMI2cW_td2TgQMV-4JaBR0m5QJ-EAAYASAAEgIC__D_BwEUR3E Ultra-Lightweight, Compact Cobot.
22. Rouzbeh, B., G.M. Bone, and G. Ashby, *High-Accuracy Position Control of a Rotary Pneumatic Actuator.* IEEE/ASME Transactions on Mechatronics, 2018. **23**(6): p. 2774-2781.
23. van Varseveld, R.B. and G.M. Bone, *Accurate position control of a pneumatic actuator using on/off solenoid valves.* IEEE/ASME Transactions on Mechatronics, 1997. **2**(3): p. 195-204.
24. White, I., Gregory Von, et al., *An Overview of Basic Radiation Effects on Polymers and Glasses.* OSTI, 2013.
25. *Hanford Tank Waste Management*. [cited 2023 11/03/2023]; Available from: ecology.wa.gov/waste-toxics/nuclear-waste/hanford-cleanup/tank-waste-management.

26. *Standard for the Selection of Non-Metallic Materials in Contact With Tank Waste*. 2021, Washington River Protection Solutions: Richland, WA.
27. Rosinha, I.P., et al., *Topology optimization for biocatalytic microreactor configurations*, in *Computer Aided Chemical Engineering*, K.V. Gernaey, J.K. Huusom, and R. Gani, Editors. 2015, Elsevier. p. 1463-1468.