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DR1 REPORT

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Power Tool Arm Attachment for a Quadruped Spot Robot

Sponsor: Los Alamos National Laboratory

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"On my honor, as an Aggie, I have neither given nor received unauthorized aid on this academic work."

Signed: *Morgan Gullo*

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Glossary

Term	Definition
DOE	Department of Energy
EPA	Environmental Protection Agency
HCI	Human Control Interface
IMU	Inertial Measurement Unit
LANL	Los Alamos National Laboratory
PC	Personal Computer
SEA	Series Elastic Actuator
USB	Universal Serial Bus

Introduction

The Department of Energy has tasked Los Alamos National Laboratory with developing an effective and efficient remediation solution for removing hazardous waste at the Hanford Site, located in Washington State. Working alongside LANL, our senior design capstone addresses one aspect of this solution. Our objective is to design a power tool arm attachment for a Quadruped Spot Robot provided by Boston Dynamics to aid in the process of breaking down and cleaning radioactive waste on the sides of tanks.

The Hanford Nuclear Reservation was established during World War II and expanded during the Cold War to produce plutonium for nuclear weapons. This process generated 56 million gallons (212 million liters) of nuclear waste, which has now been stored in underground tanks for 70 years. Starting in 2012, one year after reaching its service life, the Washington River Protection Solutions, affiliated with the Department of Energy, raised concern when they found nuclear waste being leaked into the outer shell of one of the tanks, AY-102. [2]

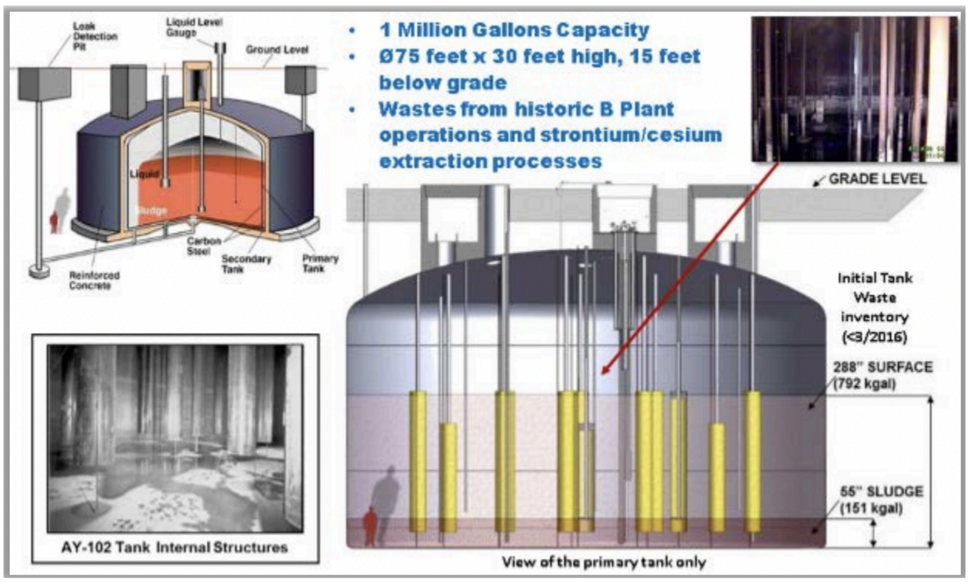

Figure 1: Tank AY-102 Overview [2]

This incident highlighted the need for urgent remediation solutions to prevent further environmental contamination, potentially contaminating the Columbia River nearby. In response, the waste needed to be safely moved to a more secure tank and it had to be done in less than 36 months. This short timeline introduced numerous challenges, as transferring radioactive waste between double-shell underground tanks had never been attempted. Transportation of this waste now requires new and innovative equipment. [3]

The primary technique that is being used by the Department of Energy (DOE) to collect and transport the waste between the tanks is known as the slurry method. This process involves mixing the radioactive liquid waste with additives to create a slurry consistency that can be treated through many drying, incineration, and compaction methods. Although this method is straightforward and reliable, it has several limitations. One major limitation is that the slurry method struggles to break down large solid chunks of waste, resulting in inefficient displacement rather than effective removal. This issue highlights a critical problem: there are currently no effective techniques that can remove the waste without significantly increasing its overall volume and price.

Beginning in 2022, the Dry Retrieval process was identified to have a significant impact on speeding up the process of removing the tank waste. However, this process required large infrastructure upgrades, costing up to 1 billion dollars. In response, the focus is now on identifying temporary, modular, and lower-cost systems with an increase in effectiveness. The approach of this process is to break up the waste, transport it to a central location, and finally remove it from the tank [9]. Our capstone encompasses the first step of this process, breaking up the waste.

Our capstone team is composed of four mechanical engineering students: Izzy Baumler, Dalton Boeckmann, Jade Waldron, and myself. We are also working closely with David Mascarenas who is the representative from LANL. The ideal mobility and kinematics of the arm is to be able to resemble a human arm, encompassing six degrees of freedom. There is also a need to deploy a wide variety of power tools attached at the end including vibratory cutters, grinders, brushes, wire wheels, sanders, vibration chisel scalers, and possibly drills. A conceptualized model can be seen below.

Figure 1: Conceptualized Model of Robotic Arm on Spot Robot [9]

The idea is that this mechanism will be able to clean the waste off the sides of the tank effectively through various terrain conditions, whether that be through a peanut butter-like consistency to hard rock. Because of the wide variety of consistency, the robotic arm must be able to exert various levels of force to be able to break up the substance presented at the wall. Designed by the capstone group, it is planned that a human will operate the machine through a human control interface. Regarding visibility, the team assumes that the technician will be able to operate the device with complete visibility while the device is in the tank. Overall, this project aims to minimize all risks of furthering the leaks present in the tanks and reduce the potential environmental impacts of leaking radioactive waste.

Background

In designing a 6-DOF robotic arm, there is a great need to introduce techniques that effectively meet the need to remove waste from hazardous tanks efficiently and safely. Through the development of the design, background research is necessary in order to provide a basis for making smart design decisions. The goal of this background research is to explain ways to incorporate passive force control and human control interface to the robotic arm in order for the robot to safely and efficiently clean the sides of the tanks.

Passive Force Control

One concept that is anticipated to be incorporated into our design is the concept of passive force control. This is to be included to minimize the potential to damage the walls of the confined spaces when using the robotic arm. Passive force control is an open-loop control system with no means to adjust for force errors [5]. An example of a hybrid force control system that combines passive mechanical compliance with active control techniques that could be used is series elastic actuators (SEAs). SEAs (Series Elastic Actuators) are designed for precise force control in high-power motors by incorporating a spring element that acts as a buffer. [6] This type of application is specifically required for impedance control, where delivering forces with a high level of safety and accuracy is essential. In the case of our project, avoiding all damage to the sides of the tanks and especially not puncturing them is our top priority. Ensuring that the robotic arm can precisely control the amount of force it is exerting is essential because insufficient control could cause additional leaks rather than resolving the existing issues. The core feature of SEAs is a spring-like elastic element positioned in series with the actuator, which absorbs and regulates force during interactions. This elastic element can act as a buffer between the motor itself and the load it is applying. This element absorbs forces while enhancing measurement accuracy. The spring's deformation is directly proportional to the force exerted, making it easier to control the interaction with external objects. An important design parameter is the spring stiffness, which directly affects the SEA's compliance and force control capabilities. [10]

Human Control Interface

In controlling the robotic arm, the use of a Human Control Interface is going to be incorporated to allow humans to interact with and control the robot arm. The use of HCI provides a user-friendly and efficient way for humans to input commands, receive feedback, and control the robotic arm to achieve the desired position and movement. Possible HCIs include traditional input devices like joysticks or handheld controllers. These are traditional ways to manually input operations by manipulating the arm in various directions through the use of switches, buttons, triggers, and thumbsticks. A way to control the robotic arm through a controller would be to use a wireless connection. This can be accomplished by using Bluetooth, wifi, or a radio frequency. A Bluetooth-enabled gamepad could potentially control a robotic arm using a Bluetooth module that is connected through a microcontroller. Ideally, a Playstation 4 or an Xbox controller can be used to begin controlling the arm itself. Other components that will need to be included are a USB Host Shield, a Bluetooth adapter, and an Arduino IDE. The USB Host shield will allow you to plug in a Bluetooth adapter and use the controller in wireless mode. The shield will then be connected to your Arduino board. Once everything is connected, the controller will need to be programmed to the specific functions of the arm. Some examples include the left stick moving in the Y direction, the right stick moving in the X direction, and the X button resetting the arm to its initial position. Lastly, a power supply is needed to power the servo shield. A simple battery holder supplied with 4 AA batteries can be connected to the servo shield to provide power to the device. An example of the result can be seen below [7].

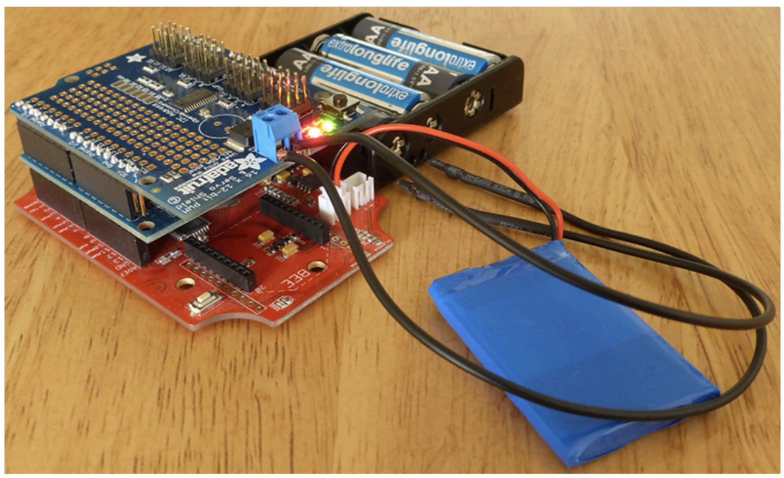

Figure 2: Electronic Model Setup for Bluetooth Controller [7]

Since the robotic arm's main objective is to resemble a human arm's functionality, the dynamic behavior would ideally be mirrored by the movement of an actual human arm. To achieve this, a sleeve that could be worn that is directly connected to the robotic arm would need to be designed and created such as a motion capture suit. Motion capture suits are full-body suits equipped with sensors that track the user’s body movements and can be adapted for controlling robotic arms. Using motion capture suits, inertial motion-tracking systems rely on a combination of small-scale inertial measurement units (IMUs), which include tri-axis accelerometers, tri-axis gyroscopes, and tri-axis magnetometer sensors. These sensors provide the 3D pose of the human body segment that it is mirroring. IMUs can then transfer processed or raw sensor measurement data to a controlled PC, where it is used for further data fusion and human-motion visualization [8]. Below is an example of how a human arm can be translated into a kinematic model and how it can be translated using an arm tracker.

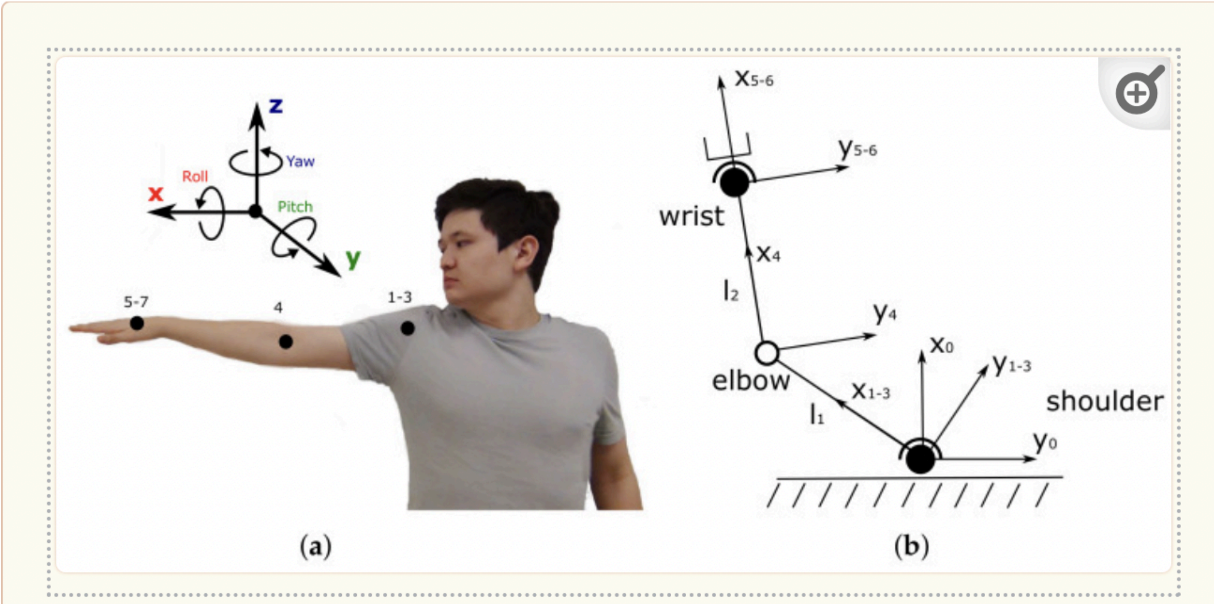

Figure 3: (a) A human arm relative to a fixed global frame with indicated DOFs; (b) a simplified human kinematic model [8]

The image below shows a 4-DOF device connected to a human arm along with the captured arm trajectories in the x, y, and z directions.

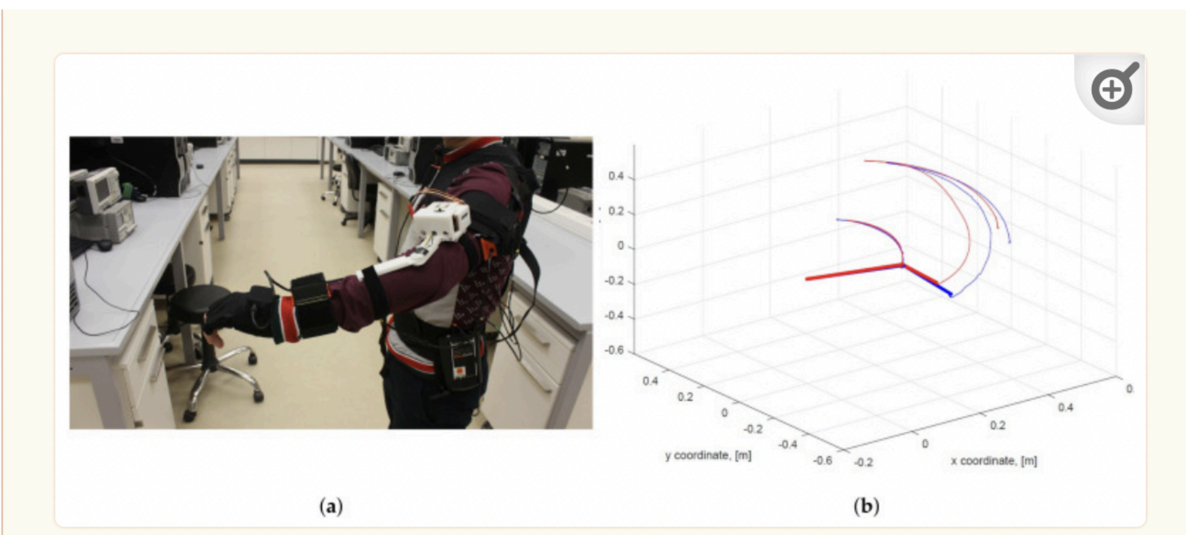

Figure 4: (a) 4-DOF arm tracker system prototype; (b) captured arm trajectories [8]

Problem

Through the initial steps in starting this project, our team was able to gather information and resources to create a mission and solution-neutral problem statement. Defining a clear, solution-neutral problem statement ensures the team remains focused on developing an appropriate solution.

Solution Neutral Problem Statement (SNPS)

Overall, the solution-neutral problem statement (SNPS) outlines the criteria for a successful design capable of achieving the goals of LANL's 6 degrees of freedom robotic arm with power tool attachment capability. Our SNPS is as follows; There should be such a technology that can efficiently and effectively manage and remove radioactive waste in extreme operation conditions without causing damage to the environment or pre-existing contaminant systems.

Mission Statement

The chart below can clarify the avenues established within our mission statement.

Table 1: Mission Statement

Mission Statement: LANL Power Tool Arm Attachment for a Quadruped Spot Robot	
Product Description	Design a Power Tool Arm Attachment with cleaning capabilities
Key Business or Humanitarian Goals	● Effectively clean nuclear waste from Nuclear Waste Tanks to prevent contamination of local environments and populations ● Successfully Prototyped and Fabricate Robotic arm within 8 months
Primary Market	Department of Energy
Secondary Market	● US Government ● US Military ● Nuclear Energy
Assumptions	We can assume: ● the robot can withstand harsh radioactive environments ● the robot can handle large amounts of force without tipping over ● the robot can handle large amounts of force without damaging the tank wall

	• visibility will allow for sensors to determine if plutonium is being removed • we assume the material is a hard tar heel substance
Stakeholders	• Washington Citizens • National Research Labs • Department of Energy
Avenues for Creative Design	• Cleaning attachments • design of arm movement/control • Semi-Autonomous
Scope Limitations	• Resources • 4 group members • 8 months to work • No Boston Dynamics robo dog to experiment with • Size limits • Force limits to protect the tank • Operation limits

In the process of creating our problem and mission statement, multiple questions were asked in order to justify them. First, the problem our team is addressing is centered around the challenges that follow the cleanup of the Hanford site. This issue of toxic and radioactive contamination being leaked through various tanks and potentially reaching the Columbia River has brought great concern to many authoritative organizations including the Washington River Protection Solutions and the Department of Energy. The key challenge involves safely and effectively cleaning up this waste material while minimizing risks to workers and the environment surrounding the area. Through this challenge, it is expected to design an advanced robotic solution that can remove the waste while being in a highly radioactive and enclosed environment. The expectations for solving this problem include designing and operating a robotic system with functionalities similar to the human arm that incorporates haptic feedback while also being operated through human control. The system must also include passive force control to prevent damaging the wall of the tanks which could lead to more waste leakage. To complete the function of cleaning the side walls, the arm must allow for power tool compatibility to attach various cleaning mechanisms to the end.

The flexibility for creative design in this project includes exploring innovative approaches in joint movements, translational and rotational devices, advanced control systems, and new waste handling techniques. These areas provide numerous opportunities for unique and effective solutions. However, the design must also account for specific requirements and limitations. Some key characteristics that need to be incorporated include achieving six degrees of freedom to mimic the motion of a human arm, ensuring seamless compatibility with the Spot robot in both physical and electrical connections, and enabling the use of various attachments, such as grinders and vibratory cutters. Additionally, the project is constrained by an 8-month timeframe and the physical challenges of operating within the tank's confined space. The design must avoid features that could compromise safety or functionality, such as damaging the container walls, being too large for the Spot robot to support, or being overly complex to operate. Balancing these requirements with the potential for creative development will be essential for achieving a successful outcome. Some technical biases that are inherent in our approach include using the Boston Dynamics Spot robot as well as the arm needing to be semi-autonomous. The technological conflicts that are presented in the initial design include making sure the arm's material can withstand radioactive exposure as well as ensuring that it can handle the tank's specific depths and conditions. We also must keep in mind that the system will have limited visibility with limited light sources and only be operated from the visibility present at the end of the arm.

Conclusion

Our capstone group is tasked with researching, designing, and creating a 6 degree of freedom robotic arm attachment alongside the Los Alamos National Laboratory in order to safely and efficiently remove hazardous radioactive waste from the side of tanks. This report outlines the essential design parameters for the robotic arm, focusing on passive force control and an intuitive human control interface to ensure safe and effective waste removal. The arm will be enhanced with human-like functionality while also including the ability to interchange tool-cleaning attachments. Some technology enhancements that are going to be incorporated into the design are the use of series elastic actuators to ensure precise force control and the use of handheld controllers to mimic the movement of a human arm. By factoring in the challenge of radioactive material and navigating within confined spaces with limited visibility, our project demands innovative solutions. Future work that will be conducted is researching and brainstorming on how all the research-specific topics generated by the team will be combined and incorporated into the arm and selecting the best criteria for each component. The team will also continue to meet with our sponsor to present weekly meetings and ensure the project is progressing in the right direction through design generation and selection criteria. By integrating advanced robotics and intuitive control systems, our team is confident that our solution will contribute to safely and efficiently remediating one of the nation's most challenging nuclear waste sites.

References/Citations

[1] *Hanford Cleanup - Washington State Department of Ecology*. ecology.wa.gov/waste-toxics/nuclear-waste/hanford-cleanup.

[2] Hanson, Carl, et al. *Hanford's Double-Shell Tank AY-102 Recovery Project – 17416*. Mar. 2017, archivedproceedings.econference.io/wmsym/2017/pdfs/FinalPaper_17416_0131032441.pdf.

[3] *2017 PMI Project of the Year Award winner: Hanford Double Shell Tank AY-102 Recovery Project*. (2017, November 1). [Video]. Youtube. https://www.youtube.com/watch?v=KEEgkAHMgRc

[4] "Treatment and Conditioning of Nuclear Waste." *World Nuclear Association*, 31 July 2024, https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-waste/treatment-and-conditioning-of-nuclear-wastes. Accessed 8 September 2024.

[5] "Force Control Basics." *PushCorp*, https://pushcorp.com/wp-content/uploads/2020/06/Force-Control-Basics.pdf. Accessed 8 September 2024.

[6] Andrea Calanca, Riccardo Muradore, Paolo Fiorini, Impedance control of series elastic actuators: Passivity and acceleration-based control, Mechatronics, Volume 47, 2017, Pages 37-48, ISSN 0957-4158, https://doi.org/10.1016/j.mechatronics.2017.08.010.

[7] "Build your own robot arm - remote control." *Jakub Staš*, 7 August 2015, https://jakubstas.com/build-your-own-robot-arm-remote-control/. Accessed 8 September 2024.

[8] Shintemirov A, Taunyazov T, Omarali B, Nurbayeva A, Kim A, Bukeyev A, Rubagotti M. An Open-Source 7-DOF Wireless Human Arm Motion-Tracking System for Use in Robotics Research. Sensors (Basel). 2020 May 29;20(11):3082. doi: 10.3390/s20113082. PMID: 32485977; PMCID: PMC7309037.

[9] Herman, David T., et al. *Dry Retrieval Report 9-25-23_ekh_DLM_AC_JP_BP_SIGNED-from-Herman-CWE.pdf*. 13 Feb. 2024, doi:10.2172/2319155.

[10] Leal Junior, Arnaldo Gomes, et al. 'Series Elastic Actuator: Design, Analysis and Comparison'. Recent Advances in Robotic Systems, InTech, 28 Sept. 2016. Crossref, doi:10.5772/63573.