TEXAS A&M UNIVERSITY

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Kinematic and Dynamic Considerations for the Design of a 7DoF Robotic Arm for Hazardous Waste Management

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Glossary

Acronym	Definition
DOE	Department of Energy
LANL	Los Alamos National Laboratory
DoF	Degrees of Freedom
SNPS	Solution Neutral Problem Statement

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1. Introduction

The scope of this senior design team's project is to design an advanced robotic solution for hazardous waste removal at the Hanford Site in Washington State. The Hanford Site, among its 45-plus years of plutonium production, has generated more than 56 million gallons of mixed hazardous and radioactive waste. The storage tanks for this waste were designed with a shelf life of 25 years but have already outlived expectation; which has caused more than 68 tanks to be in critical condition. With this increasing issue Los Alamos National Laboratory (LANL) has imposed a design challenge for four mechanical engineering students at Texas A&M university to design a 7 Degree of Freedom (DoF) robotic arm that will attach to a quadruped robot and perform cleaning operations to help break up and remove solidified waste.

The main problem at the Hanford Site is how to address the containment and removal of the nuclear waste, that has already solidified into a crystallized-salt structure. The Department of Energy's Environmental Impact Statement underlines the disastrous impact of every possible leak of these currently deteriorating tanks by again raising the degree of urgency for ingenious engineering solutions. Historically, the DOE has taken steps to stabilize the Hanford tanks by removing as much liquid waste from the tanks as possible to avoid leakage. [1]

However, recovering the remaining solidified waste is still a formidable technical task. These tanks were not originally designed for waste retrieval process, and the access points are only about one foot in diameter, which greatly restricts the size of equipment that can be used. Furthermore, the high radioactivity calls for remotely operated equipment that many times has failed under harsh conditions inside these tanks. All these challenges have pointed to the need for a solution that is more robust and efficient. The team has been tasked, under the guidance of Dr. David Dennis Lee Mascarenas from Los Alamos National Laboratory, with designing a 7-degree-of-freedom robotic arm attached to a quadruped robot to perform cleaning activities inside these hazardous waste tanks.

Dr. Mascarenas brings expertise in both robotics and environmental remediation needed to address engineering designs to help improve the harsh conditions inside these tanks. Therefore, the robotic arm proposed will be expected to break through the existing barriers of retrieving waste in a more efficient and safe way. This project targets minimizing the risk of further leaks with reduced potential environmental impact by improving the process of waste removal. This design review encompasses the background research done specifically on the design process of the 7 DoF robotic arm, the teams problem statement, and conclusions for future work on the project. First, the background research that follows provides foundational knowledge in current techniques on calculating the kinematic and dynamic behavior of industrial robots in hopes of using it for further application for our specific project.

2. Background

There is a great need to introduce design for a 7-DOF robotic arm to effectively meet the needs of expelling waste from hazardous tanks. In light of the success of this design, consideration of the analysis process of the mechanical capability of a 7-DOF arm should be taken into account. This background is necessary in order to provide the grounds where informed design decisions can be made, good control strategies can be initiated, and the integration of advanced technology can be attained.

The goal of this background research is to explain and define the process of analyzing the basic principles of kinematics and dynamics of a 7-DOF robotic arms. More specifically, this will set the grounds for: 1) how the robotic arms end effectors position is described relative to its base location, 2) how possible workspace is defined from these calculations, and 3) how various mathematical calculations are utilized to relate different joint operations and its effects on the end-effectors kinematic and dynamic characteristics. In order to do this, a review of technological developments and their applications in related industries will also be presented with the intent of explaining and applying different advances in robotics to the team’s design. Through this research, the team will gain a better understanding of the necessary design parameters taken into account for a 7-DOF robotic arm that can meet the demands of hazardous waste management cleanup process.

Kinematics in robotics starts with analyzing the motion of the system without considering the forces causing these motions. For a 7-degree-of-freedom (7DOF) robot, understanding kinematics is crucial for determining how each joint movement affects the position and orientation of the robot's end-effector. The coordinate systems and reference frames attached to each link are fundamental for modeling a robot's geometry. The Denavit-Hartenberg (DH) convention is a widely-used method for defining these frames and the transformations between them.

Denavit-Hartenberg (DH) convention is used to simplify the process of defining and calculating joint and link parameters. The DH convention is a method for assigning coordinate frames to each joint and link of a robot manipulator (see Appendix A). The final DH parameters are then used to form the homogeneous transformation matrices, which describe the position and orientation of the end-effector, in our case the cleaning attachments, relative to the base frame [6]. This convention ensures that despite changes in reference frame assignments, the final transformation matrix remains consistent, making it easier to simplify kinematic equations and understand the end-effector's location.

For a more comprehensive understand there was a recent study done for the design and experimentation of a clamping robot that utilizes a 6DOf system to pick apples off of a tree [3]. The teams started with an analysis of the Denavit-Hartenberg (DH) convention on each of the joints as seen in ***Figure 1***.

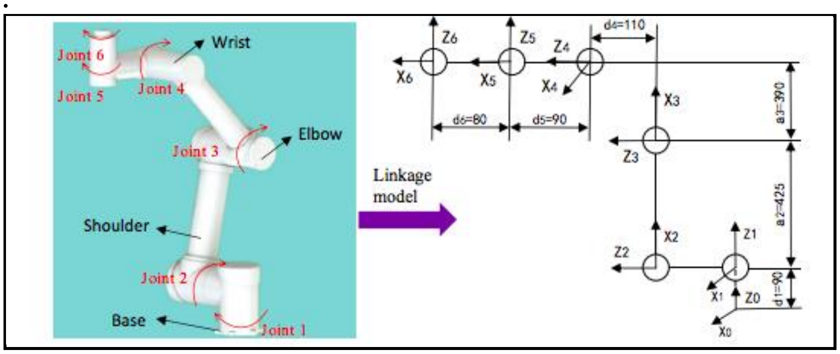

Figure 1: Linkage Model for Apple Picking Robotic Arm [3]

Through this analysis the team then used the mathematical model explained by the Denavit-Hartenberg (DH) convention to tabulate the results for the four parameters: link length (a_i), link twist (α_i), joint offset (d_i), and joint angle (θ_i). This tabulation can be seen in ***Table 1***.

Parameters of the apple-picking robot

i	α_i / (°)	a_i / mm	d_i / mm	θ_i/(°)	Variable Range
1	90	0	90	θ_1	-360~360
2	0	425	0	θ_2	-90~90
3	0	390	0	θ_3	-180~180
4	90	0	110	θ_4	-30~30
5	-90	0	90	θ_5	-90~90
6	0	0	80	θ_6	-90~90

Table 1: Denavit-Hartenberg Parameters for Apple Picking Robotic Arm [3]

From this study the team then utilized the basics for a homogeneous transformative matrix (See Appendix B), to compute the transformative homogenous matrix with respect to each joint. Through the team utilized a process known to determine the end effectors position and the orientation with respect to the base coordinate system of the robot, so in this example where the robotic arm is connected to ground. This process is called forward kinematics and utilizes the parameters defined by the Denavit-Hartenberg, as seen below:

Equation 1:

$$ {}^{i-1}_{i}T = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Once this transformative matrix was performed with respect to each joint and its Denavit-Hartenberg parameters the forward kinematic calculation was performed to derive a system of equations relating the orientation of the end effector to the bases coordinate system.

Equation 2:

$$ {}^{0}_{6}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T\,{}^{3}_{4}T\,{}^{4}_{5}T\,{}^{5}_{6}T = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

The forward kinematic calculations result in several key outputs: *n*,*o*,*a*, and *p* each providing crucial information about the end-effector's position and orientation. The matrix output from these calculations includes the position vector *p*, which specifies the end-effector's location relative to the base frame in 3D space. Specifically, *n* denotes the direction cosines that align the end-effector's coordinate system with the base frame's axes, while *o* reflects the rotational offsets. The parameter *a* represents the link length, which affects the distance between joints and thus the overall reach of the robot. [4] By combining these elements, the transformation matrix provides a comprehensive description of the end-effector's position and orientation, allowing for a comprehensive analysis of the robot's available workspace [3].

This application is crucial in understanding the design process for the teams 7DOF system robotic end effectors, cleaning tools, position with relativity to its base. From this the team will be able to denote the applicable cleaning space in which the robotic arm attachment will be able to operate and clean. To transition from a task space defined by the Denavit-Hartenberg (DH) convention to an action space (velocity of end effector), there is a mathematical computation used to understand the effects of the joints velocities on its end effectors velocity that will intern control the cleaning time and the dynamic capability of the robot. This can be calculated through a process utilizing a Jacobian Matrix solving process (see Appendix C) [4].

The Jacobian matrix is used to map joint velocities to end-effector velocities, ensuring precise control of the robot's speed and accuracy during operations. The Jacobian matrix helps in defining the cleaning space by indicating how each joint's motion affects the position and velocity of the end-effector in relation to the robot's base [7]. This is particularly important for a robot with 7 degrees of freedom, as it offers extra flexibility, known as redundancy, allowing multiple configurations to achieve the same end-effector position and operation [6].

In transitioning from kinematic to dynamic behavior, the Jacobian matrix becomes crucial for force control. It maps joint torques to the forces exerted by the end-effector, enabling the robot to handle delicate cleaning tasks by ensuring controlled force application [6]. This is especially useful when passive force control is employed to prevent damaging the tank walls during cleaning [4]. Additionally, the Jacobian matrix aids in redundancy resolution, helping optimize joint configurations to avoid unnecessary energy use, joint limits, or obstacles in confined spaces like nuclear waste tanks [6].

The significance of this research will become evident as the project progresses. The team will utilize simulation and real-time modeling to analyze the motion of the 7-degree-of-freedom robot arm. Understanding and Utilizing these concepts is not purely theoretical; it forms the basis for optimizing the robot's design parameters, creating efficient control systems, and integrating advanced technologies like passive force control.

3. Problem

3.1. Solution Neutral Problem Statement (SNPS):

The solution neutral problem statement (SNPS) is a statement that describes what must be done for the completion of the LANL 7 DoF robotic arm attachment to be successful. Through a comprehensive team analysis, the SNPS was drafted to outline the requirements that need to be met to ensure success. The SNPS is as stated; There should be such a technology that can efficiently manage and remove radioactive waste in extreme operation conditions without causing any damage to the environment or pre-existing containment systems.

3.2. Mission Statement:

The team's mission statement is to design and prototype a robotic power tool arm attachment for the Spot quadruped robot, with cleaning capabilities catered for the removal of nuclear waste from expired tanks. The teams goal is to prevent contamination of local environments, achieve a functional prototype within 8 months, and develop a sustainable solution for the LANL to undergo hazardous waste management processes. This can be seen further outlined in ***Table 2***. The table allows for a overall description of the scope of the project while taking into account various parameters.

Table 2: *Outline of the LANL Teams Mission Statement with key influencing Factors*

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, only 4 group members, only 8 months to work on it, No Boston dynamics robotic dog to work with, Size limits, Force limits to protect the tank, Operation limits

3.3. Justification of Problem Statement and Mission Statement

***Table 3**: Justification for the Problem Statement and Mission Statement*

Technical Question	Explanation and Justification
1. What is the problem really about?	The problem involves managing and removing hazardous radioactive waste from aging storage tanks at the Hanford Site. The waste has solidified, creating significant environmental and safety risks. The challenge is to design an advanced robotic solution for hazardous waste removal that can efficiently perform this task in a highly radioactive and confined environment.
2. What implicit expectations and desires are involved?	Implicit expectations include the need for a solution that addresses immediate waste management issues while adhering to safety and environmental standards. There is a need for a robotic arm that can operate effectively in harsh conditions and adapt to various ergonomic situations.
3. Are the stated customer needs, functional requirements, and constraints truly appropriate?	Yes, the design must ensure effective waste removal, minimize environmental impact, and operate safely within the tank's constraints. Constraints such as limited space, high radioactivity, and the need for remote operation are crucial considerations and align with the mission's goals. All of these constraints are appropriate.
4. What avenues are open for creative design? Limitations on scope?	Creative design avenues include exploring innovative on joint movements, translation and rotational devices, control systems, and new waste handling techniques are all potential areas for innovation. Limitations include the project's 8-month timeframe, 7 DoF design, and the physical constraints of operating within the tank's confined space.
5. What characteristics/properties must the product have (and not have)?	The robotic arm must be easily operatable, precise, and capable of handling nuclear waste The arm should not be overly complex to operate and or fragile.
6. What aspects of the design task can and should be quantified now?	Aspects that can be quantified now, due to the research, include the required torque levels for each joint, an estimation on the maximum force the arm can handle without tipping, the operational workspace, and the speed of action. These parameters are crucial for defining the arm's performance and ensuring it meets the operational requirements for waste removal.
7. Do any biases exist with the chosen task statement or terminology? Has the design task been posed at the appropriate level of abstraction?	The task statement is generally unbiased and appropriately abstract, focusing on the need for an efficient waste management solution without specifying technologies. The only abstract problem the team ran into as the focus on the cleaning tool attachments priority in comparison to the robotic arm, however through Communication with Dr. Mascarenes this was clarified and resolved.
8. What are the technical and technological conflicts inherent in the design task?	Technical conflicts include balancing the arm's strength and flexibility with size constraints as well as constraints imposed by the quadruped. As well as, the amount pf torque that can be applied so that it doesn't infringe on the operation of the spot robot. Technological conflicts involve developing a control system capable of handling the arm's complexity while ensuring that it is easy to operate. Addressing these conflicts requires careful design choices and collaboration with Los Alamos Nation Laboratory and our Sponsor.

4. Conclusion

The Texas A&M engineering capstone team has been tasked by the Los Alamos National Laboratory to research, design, and fabricate a 7 Degree of Freedom robotic arm attachment for a quadruped robot to perform hazardous waste management processes. The research encompassed in this report allowed for a comprehensive understanding of the kinematic and dynamic analysis that needs to be made to make precise decisions on the control of arms movement and force applications. It is also important to note that this analysis, will also simplify the process of determining the appropriate; torque levels for each joint, how much applicable force the robot can undergo, the performance space of the robot, and how fast the robot can perform. This research has outlined that the team will begin by analyzing the necessary number of joints for the quadruped robot attachment and use the Denavit-Hartenberg convention to examine the position of the end effector concerning the base, and then calculate and analyze the Jacobian matrices to define the end effectors velocity and the influence the joints torques have on the end effectors dynamic behavior. Research and application of this chosen technique will be verified with LANL professionals to continue to fulfill and meet the goals outlined in this report. Future work will include the continuation of research on the Kinematic and Dynamic Considerations as well as coming together with other group members on their research-specific topics to come together and work towards our end goal. Lastly, the team will ensure the project is on track by continuing weekly meetings with Dr. Mascarenes, emphasizing and adapting areas of focus when needed, and resenting weekly updates.

5. Appendices

Appendix A: Denavit-Hartenberg (DH) Convention

According to the DH convention, each link and joint is represented by a set of four parameters: link length (a_i), link twist (α_i), joint offset (d_i), and joint angle (θ_i). The process begins with assigning coordinate frames such that the axes z_i), are aligned with the joint axis of each link. If joint i+1 (the joint following the joint being analyzed) is revolute, z_i), is the axis of rotation; if prismatic, z_i is the axis of translation. The base frame is established with its origin on $z_0$and the x_0 and y_0 axes chosen to form a right-handed system [4]. For each subsequent frame, three cases are considered based on the relative position of z_{i-1} (the previous joint axis): they may be non-coplanar, parallel, or intersecting. Each case requires specific methods to determine the x_i and y_i axis to ensure the transformation matrices are accurate [4].

Appendix B: Homogenous Transformative Matrix

The homogenous transformative matrix allows for one joint to denote its position with respect to another joint. This understanding is crucial in order to perform forward kinematic calculations.

Appendix C: Jacobian Matrix Calculation

The Jacobian Matrix is made up of all the first order partial derivatives of a vector function. On a clearer note, every element that is within the matrix represents a partial derivative of a component of the outputted vector. In the LANL teams case, we would have a 6x7 matrix, due to the rows accounting for the linear and angular velocities, where the columns would represent the joint velocities at each of the 7 joints.

5. References

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