Mars Sample-Return Rover

ENPM 662 Final Project

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1 Abstract

Space exploration is still a topic of interest because technology is continuously developing. Exploring and researching Mars is the most convenient way to trial and test new space technologies since it is the closest planet to Earth that is able to conduct research on. NASA approached Mars exploration through the Sample-Return Rover, a robot that can explore unknown terrain autonomously and be able to collect samples. The earliest primitive model was launched in 1997, and the latest one being 2020 with the Curiosity Rover. This project focuses on recreating the earlier version of the rover in SolidWorks and being able to simulate the exploration in a 3D environment with Gazebo.

2 Introduction

This project focuses on the Mars Sample-Return Rover, developed by NASA's Jet Propulsion Laboratory (JPL). Exploring the unknown is fascinating with the challenges that are present. Robotics is a field suitable to approach these challenges because they have the capability to operate autonomously. The model will be created in Solidworks and then simulated in Gazebo. The report explains the elements of the project, starting with the rover's geometric aspects such as its mechanical design, joints, links, and arm. The rover consists of the vehicle base with the chassis and wheels, and an attached four degree-of-freedom (4DOF) arm.

The rover's chassis has an interesting structure with the front and rear links are connected with one joint, but have independent movement. With a total range of 180 degrees, the rover can scale steep cliffs because of the design. The front wheels can also rotate side-to-side so that the rover can turn. Attached to the chassis is a 4DOF arm. It rotates at its base, an elbow joint, and the wrist joint can rotate sideways and and up and down. The end-effector on the arm allows for sample-collection.

With the challenges of unknown terrain and inability to remote control the robot, extensive research and testing has to be made before launching the robot. The scope of this project focuses on the Sample-Return Rover. Model assumptions will be discussed. Afterwards, the design of the robot will be explained with analysis of the kinematics of the vehicle and the arm.

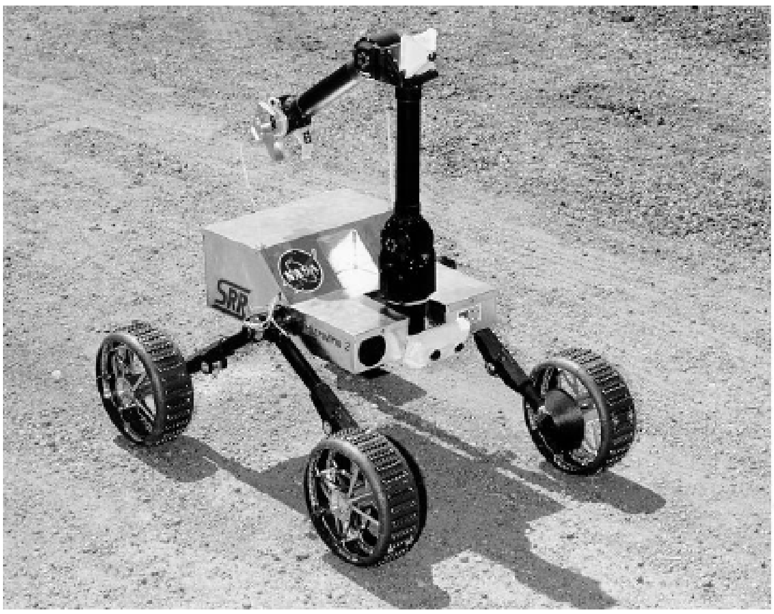

Figure 2.1: Early Model of the Sample Return Rover

3 Motivation

Space robotics is a big area of interest. Not only has there been the Sample-Return Rover, but there is also the CubeSat, BioSentinel, and many others. The Sample-Return Rover is a great choice for this project as the information gained from the class will be used on the rover. There are many possible usages for space robotics. They can serve the purpose of exploring unknown territory, surveillance of the Earth, or maintenance on existing robots/satellites.

Each different type of robot will deal with their own challenges, whether it is dealing with low or zero gravity, extreme temperature changes, or rocky terrain. It is amazing how diverse space robotics can be. The area of research is vast and takes much effort to be in a robotics field. The intention of this project is to get an introductory hands-on experience with both mobile robots and a manipulator simulation. Calculating forward, inverse, and velocity kinematics are a big topic for this project, as well as implementation of those calculations into algorithms.

4 Assumptions

Since the scope of this project deals with simulating a robot in outer space, there are assumptions to be made because certain things cannot be measured easily. To deal with this issue and other design factors, there are assumptions to follow.

1. The robot is a rigid body, any torque or force acted upon any link will not be deformed.

2. The steering design is based off the Ackermann-Steering model.

3. All motion or revolution will be around the z-axis.

4. The simulations will be in Gazebo and RVIZ.

5 Robot Design

The robot base comprises of four legs, with two on each side that are concentric. On either side, two of the legs are connected via a revolute joint and is concentric. The front wheels have a revolute joint connected to the wheels so that the robot can steer left or right. To have the robot at the same height, the rear wheels have the same joint however it is fixed. The robot arm that is attached has four degrees of freedom.

Modeling the robot is split into the vehicle and arm separately. With this method, both models can be configured and tested properly in Gazebo in order to use tele-op on individual joints. Figure 5 shows the rover modeled in SolidWorks. Table 5.1 lists the dimensions of the robot and links. Figure 5 and Figure 5 are images of the arm for reference.

Link	*Length*
Chassis Length	18in
Chassis Width	12in
Chassis Max Height	7in
Leg from Center Joint	8.6in
Length of Steering Link	5.25in
Wheel Diameter	7.5in
Wheel Track	19.3in
Wheelbase	13.9in

Table 5.1: Table of Dimensions of the Rover

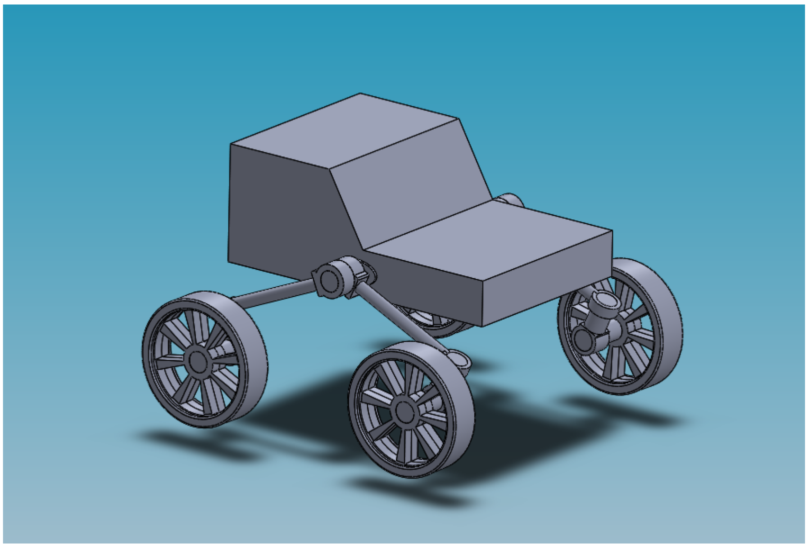

Figure 5.1: Sample Return Rover in SolidWorks

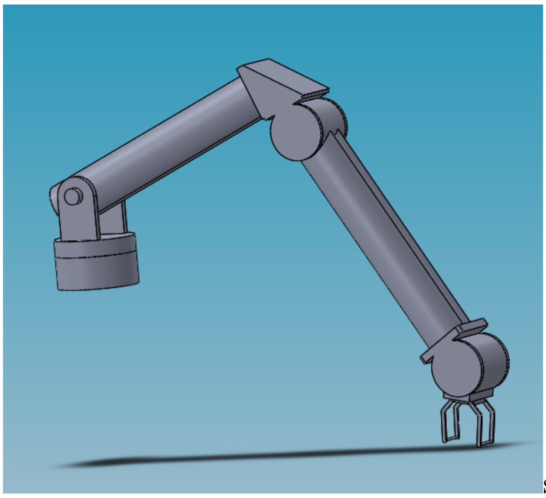 s

Figure 5.2: Arm Model in SolidWorks

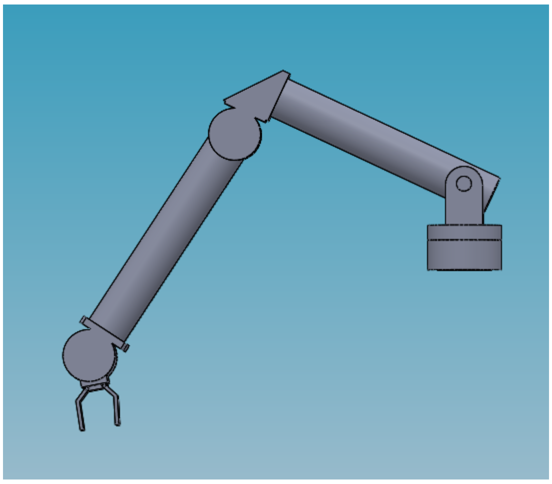

Figure 5.3: Side View of Robot Arm

Forward Kinematics

Vehicle

The rover uses an Ackermann steering mechanism to be able to navigate. Unlike a manipulator, it is not a serial connection. Forward kinematics cannot be used on a mobile robot. Ackermann steering allows the front wheels to rotate independently, about a common center point. This center point is called the *Instantaneous Center of Curvature* (ICC). In general, it uses a four bar linkage in a trapezoidal shape. However the Curiosity Mars Rover and the Sample-Return Rover does not use this linkage, but the model still holds.

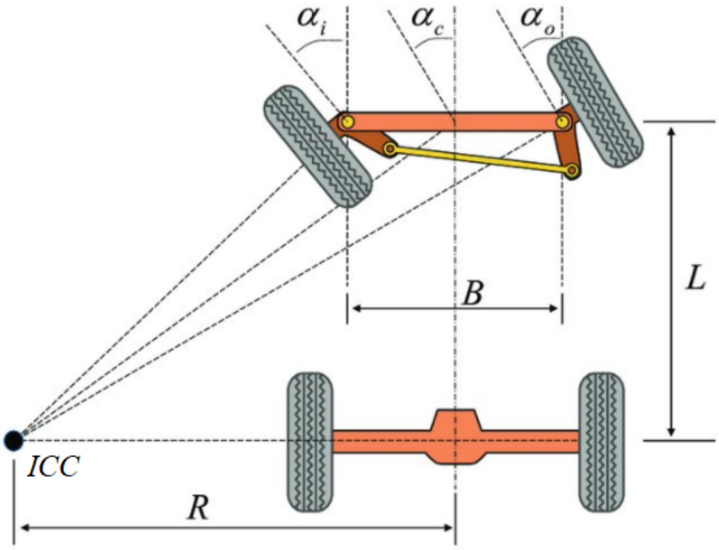

Figure 5.4: Diagram for Ackermann Steering

Arm

In robotics, forward kinematics is used to find the position and orientation of the robot's end-effector (or gripper) given the joint angles. In this course, joints can have two different types: *revolute* and *prismatic*. A revolute joint rotates about an axis. A prismatic joint translates linearly along an an axis. A robotic arm can be considered as serial kinematic chains, because starting from the base of the arm the rest of the joints and links position are dependent on its parent joint and link orientation. Each joint can be assigned a coordinate frame with an x, y, and z axis. These frames represent either rotations or translation at a joint it is assigned to. These frames and their rotations/translation can be represented with a 3x3 matrix, which can then be put in a homogeneous transformation matrix and chained together to find the position of the end-effector.

The robot arm itself has 4 degrees of freedom, with it all being revolute. However, there are 8 frames in total, because 4 dummy frames are for Gazebo to properly render in the arm. The frames are shown in Figure 5.1.2. Its corresponding DH table is shown in Figure 5.2. A list of the links are shown in Figure 5.1.2. The links LeftFinger and RightFinger are just there for Gazebo to be able to rotate the end-effector fingers, but they are not used in the DH parameters and table.

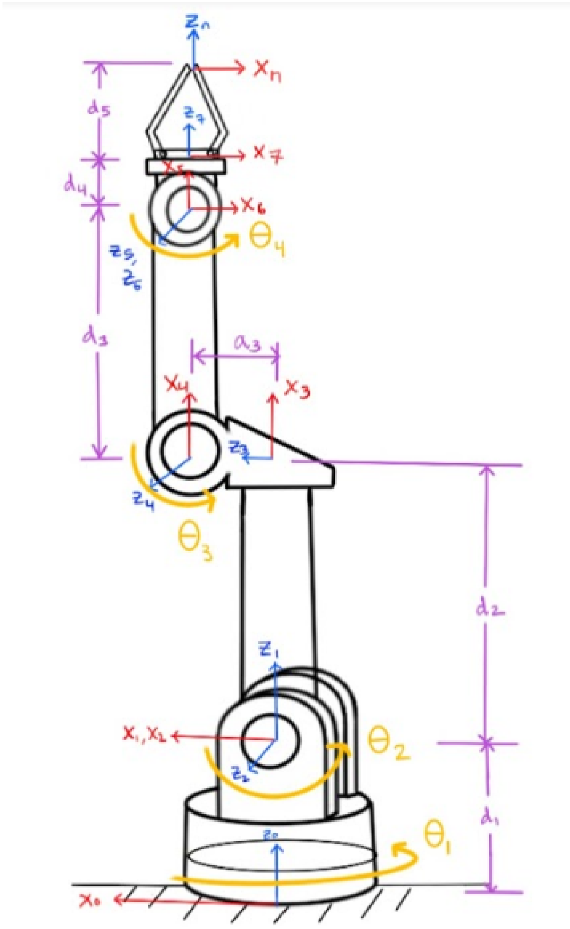

Figure 5.5: DH Frames of the Arm

Link i	θ	d	α	a
1	θ_1	d_1	0	0
2	0	0	-90	0
3	θ_2 - 90	0	-90	d_2
4	0	a_3	90	0
5	θ_3	0	0	d_3
6	θ_4 - 90	0	-90	0
7	0	d_4	0	0
n	0	d_5	0	0

Table 5.2: DH Table for the Arm

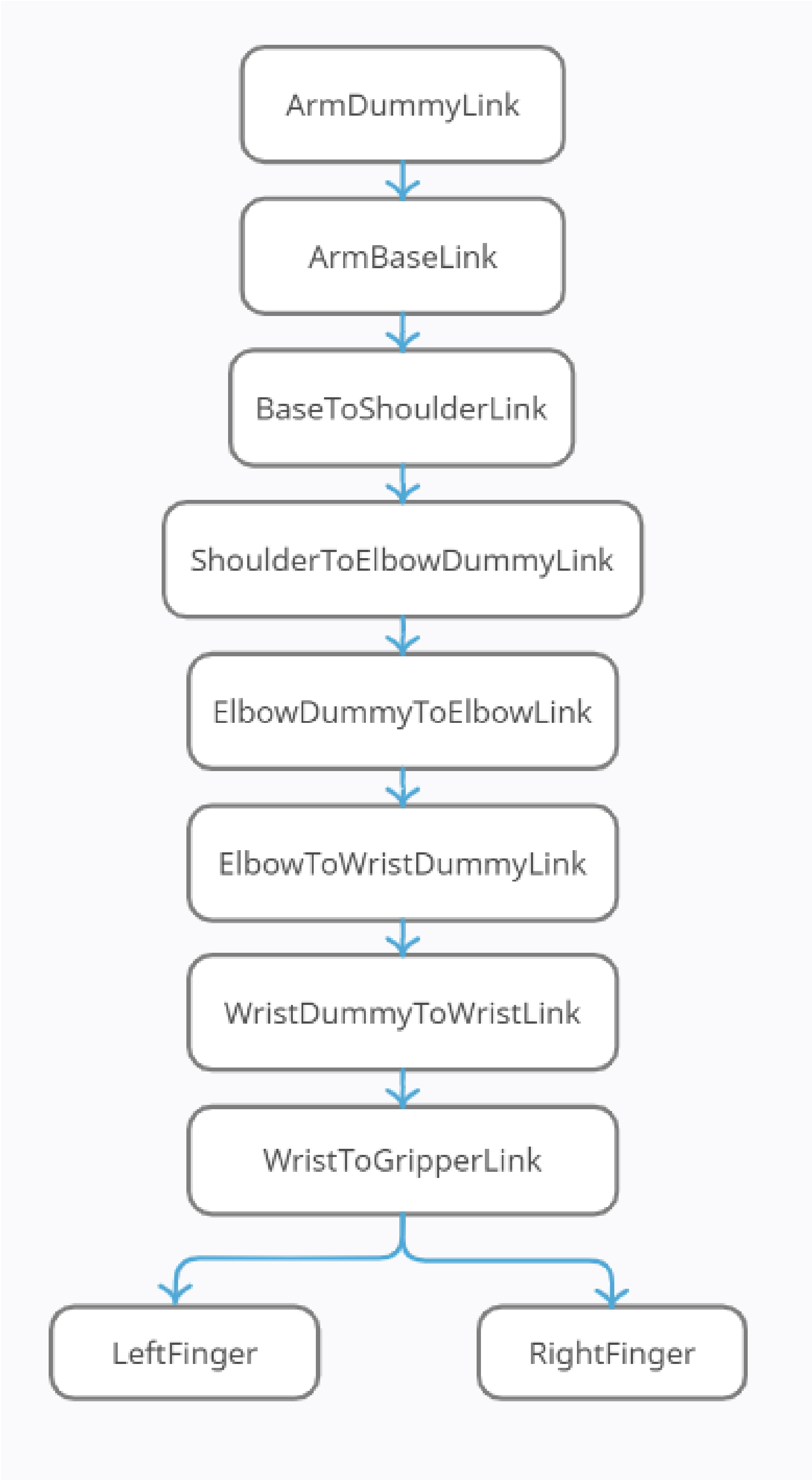

Figure 5.6: Flowchart of the Arm Links

To start calculating the forward kinematics, rotation matrices can be made for the frames. The basic rotation matrix for a rotation about the z-axis with an angle θ can be shown in Equation 5.1. Using the DH Table, the homogeneous transformation matrices can now be written. The setup for this matrix is seen in Equation 5.2.

$$R_{z,\theta} = \begin{bmatrix} cos(\theta) & sin(\theta) & 0 \\ sin(\theta) & cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{5.1}$$

$$H_n^0 = \begin{bmatrix} R_n^0 & d_n^0 \\ 0 & 1 \end{bmatrix} \tag{5.2}$$

To find the position and orientation of the end effector by using the homogeneous transformation matrices the distances between each frame needs to be defined. Table 5.3 defines all the lengths needed between the frames in regards to the CAD model.

Distance between Frames	*Length*
Base to Frame 1 (d_1)	2.9in
Frame 2 to Frame 3 (d_2)	7.73in
Frame 3 to Frame 4 (a_3)	1.76in
Frame 4 to Frame 5 (d_3)	8.93in
Frame 6 to Frame 7 (d_4)	1in
Frame 7 to Frame n (d_5)	1.41in

Table 5.3: Table of Link Lengths of the Arm

Note that the arm's home position starts with all angles being at 0, so the arm is fully upward. Each joint has a limit for its range of motion so that the robot does not crash into itself. This can be seen in Equations 5.3 - 5.6.

$$\theta_1 = [-\pi,\ +\pi] \tag{5.3}$$

$$\theta_2 = \left[\ 0,\ +\tfrac{2\pi}{3}\ \right] \tag{5.4}$$

$$\theta_3 = [0,\ +\pi] \tag{5.5}$$

$$\theta_4 = \left[\ -\tfrac{2\pi}{3},\ +\tfrac{2\pi}{3}\ \right] \tag{5.6}$$

The final homogeneous matrix can be also written as Equation 5.7:

$$H_n^0 = \left[\begin{array}{ccc} x_n^0 & y_n^0 & z_n^0 \end{array} \right] \tag{5.7}$$

where

$$x_n^0 = c_1 \left[\begin{array}{c} d_2 s_2 + a_2 c_2 + d_3 s_{23} + (d_4 + d_5) s_{234} \end{array} \right] \tag{5.8}$$

$$y_n^0 = s_1 \left[\begin{array}{c} d_2 s_2 + a_2 c_2 + d_3 s_{23} + (d_4 + d_5) s_{234} \end{array} \right] \tag{5.9}$$

$$z_n^0 = \left[\begin{array}{c} d_1 + d_2 c_2 - a_2 s_2 + d_3 c_{23} + (d_4 + d_5) c_{234} \end{array} \right] \tag{5.10}$$

Note that c is cos, s is sin, and multiple numbered subscripts means they are added together. For example, s_{23} is equivalent to $(\sin(\theta_2) + \sin(\theta_3))$.

Inverse Kinematics

Arm

Inverse Kinematics is the opposite of Forward Kinematics. Given the end effector's position and orientation (the homogeneous transformation) the joint angles needs to be found. In this case H is the desired position and orientation. Equation 5.11 is the equation where one or more solutions needs to be solved in order to find the joint angles (q_i).

$$T_n^0(q_1, ..., q_n) = H_1(q_1) \cdots H_n(q_n) = H \tag{5.11}$$

Inverse kinematics can be far more complex than solving forward kinematics. In some cases an unsolvable problem will be encountered. A typical approach to solving inverse kinematics problems is called **kinematic decoupling**. Essentially it approaches the problem by breaking it down into two subproblems, with the first is calculating the position of the wrist center (intersection between the wrist axes) and then finding the orientation of the wrist center.[2]

For the arm, the easiest start is to solve for θ_1. With the desired x_n^0 and y_n^0 , the arctan(y/x) can be used.

$$\frac{y_n^0}{x_n^0} = \frac{s_1[d_2 s_2 + a_2 c_2 + d_3 s_{23} + (d_4 + d_5) s_{234}]}{c_1[d_2 s_2 + a_2 c_2 + d_3 s_{23} + (d_4 + d_5) s_{234}]} \tag{5.12}$$

The numerator and denominator cancels out. The term (s_1/c_1) can be written as $\tan(\theta_1)$. The equation is now

$$\frac{y_n^0}{x_n^0} = tan(\theta_1) \tag{5.13}$$

Now take the $\arctan(\theta_1)$ to solve for (θ_1).

$$\theta_1 = atan(\frac{y_n^0}{x_n^0}) = atan2(y_n^0, x_n^0) \tag{5.14}$$

θ_1 is the only revolution in the xy plane. Therefore after θ_1, the remaining joints turn the robot arm to a planar manipulator, meaning all the movement is parallel. Now, the equations for link i are:

$$\begin{aligned} x_n^i &= d_2c_2 + a_2s_2 + d_3c_{23} + (d_4 + d_5)c_{234} \\ y_n^i &= d_2s_2 + a_2c_2 + d_3s_{23} + (d_4 + d_5)s_{234} \\ z_n^i &= 0 \end{aligned} \tag{5.15}$$

Let's substitute $\gamma = \theta_2 + \theta_3 + \theta_4$

$$x_n^i = d_2c_2 + a_2s_2 + d_3c_{23} + (d_4 + d_5)c_\gamma$$

$$y_n^i = d_2s_2 + a_2c_2 + d_3s_{23} + (d_4 + d_5)s_\gamma$$

$$\Rightarrow x' = x_n^i - (d_4 + d_5)c_\gamma = d_2c_2 + a_2s_2 + d_3c_{23} \tag{5.16}$$

$$\Rightarrow y' = y_n^i - (d_4 + d_5)s_\gamma = d_2s_2 + a_2c_2 + d_3s_{23} \tag{5.17}$$

From here, square both equations to add them and simplify.Equation 5.18.

$$\Rightarrow (-2x'd_2 - 2y'a_2)c_2 + (-2x'a_2 - 2y'd_2)s_2 + (x'^2 + y'^2 + d_2^2 + a_2^2 - d_3^2) \tag{5.18}$$

Equation 5.18 can be compared to $Pc_\beta + Qs_\beta +$ R $= 0$ in which Equation 5.19 can be solved with γ:

$$c_\gamma = \frac{P}{\sqrt{P^2 + Q^2}}, \; s_\gamma = \frac{Q}{\sqrt{P^2 + Q^2}} \tag{5.19}$$

$$\Rightarrow \delta = atan2(\frac{Q}{\sqrt{P^2 + Q^2}}, \frac{P}{\sqrt{P^2 + Q^2}})$$

$$\Rightarrow c_\gamma c_\beta + s_\gamma s_\beta + \frac{R}{\sqrt{P^2 + Q^2}} = 0$$

$$\beta = \gamma \pm cos^{-1}(\frac{-R}{\sqrt{P^2 + Q^2}}) \tag{5.20}$$

θ_2 can be set to

$$\theta_2 = \gamma \pm cos^{-1} \tag{5.21}$$

Equation 5.20 and given γ, P, Q, and R then θ_2 and θ_3 can be solved for:

$$P = -2x'd_2 - 2y'a_2, \tag{5.22}$$

$$Q = -2x'a_2 - 2y'd_2, \tag{5.23}$$

$$R = x'^2 + y'^2 + d_2^2 + a_2^2 - d_3^2 \tag{5.24}$$

Then using Equation 5.16 and 5.17, cancel out d_3 and then divide y'/x' to get:

$$tan(\theta_2 + \theta_3) = atan2(\frac{y' - d_2 s_2 - a_2 c_2}{x' - d_2 c_2 + a_2 s_2}) \tag{5.25}$$

$$\theta_3 = atan2(y' - d_2 s_2 - a_2 c_2,\ x' - d_2 c_2 + a_2 s_2) - \theta_2$$

Remember that $\gamma = \theta_2 + \theta_3 + \theta_4$, solve for θ_4 to get

$$\theta_4 = \gamma - \theta_2 - \theta_3 \tag{5.26}$$

Finally, resolving the (x,y) coordinates of the end-effector in the i^{th} frame yields

$$[x_n^i\ y_n^i\ z_n^i]^T = P_n^i,\ [x_n^0\ y_n^0\ z_n^0]^T = P_n^0 \tag{5.27}$$

$$\Rightarrow P_n^i = T_0^i \cdot P_n^0 = (T_1^0 \cdot T_2^1 \cdot T_i^2)^{-1} \cdot P_n^0 \tag{5.28}$$

Velocity Kinematics

6 Scope of Achievement

For the scope of achievement and study, milestones and careful planning had to been made. Most of the concepts learned in this class were able to translate over to this project. A list of milestones are presented below, in order of planning and achievement.

1. Build the vehicle part of the rover
2. Create the ROS workspace environment
3. Create a terrain similar to Mars terrain in Gazebo
4. Test the vehicle URDF and tune the controls
5. Build the arm for the rover
6. Calculate and create scripts for the kinematics of the arm

7 Model Validation and Testing

Bibliography

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[3] T. L. Huntsberger P. S. Schenker and G. T. McKee University of Reading (UK) P. Pirjanian Jet Propulsion Laboratory (USA). "Robotic Autonomy for Space: Cooperative and Reconfigurable Mobile Surface Systems". In: i-SAIRAS 2001. Canadian Space Agency, St. Hubert, Quebec, Canada, 2001.