Robot-Assisted Pap Smear Tests

1. Background and Significance

The Pap smear procedure involves the collection of a small sample of cells from the cervix and the surrounding area to screen for any signs of cervical cancer or changes that may lead to it [1]. However, for many women, this process can be challenging and uncomfortable due to differences in cultural and religious beliefs or personal preferences. As a result, some women may choose to delay or even avoid this essential annual checkup, which can lead to devastating consequences. According to data from the Canadian Cancer Society, an estimated 1450 Canadian women were diagnosed with cervical cancer in 2022, and approximately 380 lost their lives to the disease [2]. These statistics underscore the importance of regular cervical cancer screenings to detect and treat the disease early.

Unfortunately, the current Pap smear procedure can be uncomfortable for women. During the examination, a healthcare provider inserts a speculum into the vagina to widen its walls and expose the cervix. The healthcare provider then collects a small sample of cells using a brush, swab, or spatula from the cervix and the back of the vagina [3]. While the Pap smear procedure remains an essential tool in the fight against cervical cancer, efforts must be made to make the process more comfortable and accessible.

Given the discomfort associated with the current Pap smear procedure, it is crucial to explore alternative screening methods that are less invasive and more comfortable for women. This approach could encourage more women to undergo regular screenings and help detect cervical cancer at an early stage when it is most treatable. That is why a robotic solution may help ease the procedure for women who may have had reservations about undergoing the procedure due to their cultural, religious or personal beliefs and help make them feel more comfortable during the screening process. Hence, by making these screening methods autonomous with the help of robot manipulators, we can work towards increasing checkups rates and to reduce the mortality rates of cervical cancer in Canada and around the world.

2. Innovation

Our team has developed a novel solution to improve the patient experience during Pap smear tests. Our robot manipulator is designed to conduct the test fully autonomously, eliminating the need for a healthcare professional in the room. This can significantly contribute to patient comfort and privacy, as well as increase accessibility for women who may not have access to qualified medical professionals. One of the advantages of our innovation is its consistency and accuracy. The robot is programmed to follow a specific protocol, ensuring that the sample collection is done correctly, thereby reducing the risk of possible human error. This ensures accurate and reliable results.

In addition, our robotic approach can save time for healthcare professionals and patients. Instead of having to schedule an appointment with a doctor and wait for their availability, patients can visit healthcare facilities equipped with our innovation to conduct their annual checkups. This is particularly beneficial for busy women who may not have the time to visit a doctor's office. Our robot also offers a more comfortable and private experience for women which in turn can help reduce anxiety and discomfort, making the experience more pleasant overall.

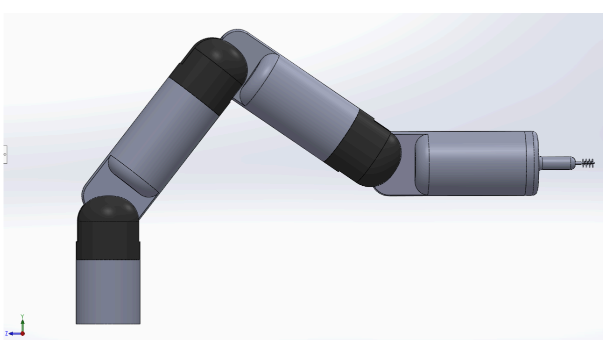
In summary, our robot manipulator for conducting Pap smear tests offers a novel and innovative solution that enhances patient comfort, increases accessibility, improves accuracy, and saves time for healthcare professionals and patients alike.

3. Design

3.1. Mechanical Design

Our innovative five-link manipulator features three spherical joints and one prismatic joint to increase accessibility in all dimensions *(Figure 1)*. The robot's arm is designed to pass through itself and the ground, creating a spherical workspace. The end effector is a small gripper that holds the sampling brush, located inside the spatula. When the spatula enters the vagina and reaches a certain depth, the prismatic joint pushes the gripper forward, but not outside of the spatula, while pushing the brush out. Once the sampling brush touches the cervix, it starts rotating slowly around its own axis with the help of the spherical joint to collect the sample. To ensure safety, a pressure sensor has been integrated into the spatula to constantly monitor the end effector's position in the vagina. In addition, a remote emergency stop button is available to allow the client to pause the robot immediately in case of emergency*.

***Note:** Design files for the CAD model can be found in the attached file, 'Revised SolidWork'.*



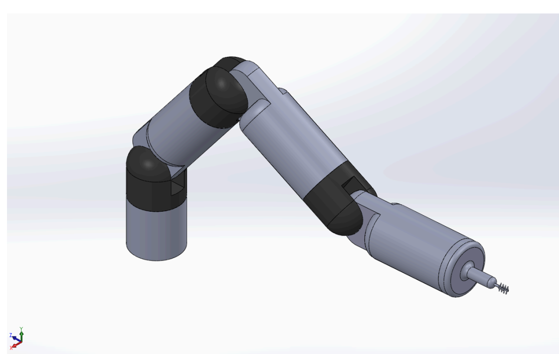


Figure 1: *The robotic manipulator designed for conducting Pap smear tests. It consists of five links and four joints, including three spherical wrist joints and one prismatic joint.*

3.2. Controller Design

The device includes a laparoscopic camera for visual feedback. There is also haptic feedback. This haptic feedback comes from force data obtained through a strain gauge sensor. This will allow the operator of the device to have a sense of how hard the device is pressing against the tissue of the patient. Having this information will help the operator to both apply sufficient force for the pap smear and to avoid applying forces high enough to cause unnecessary discomfort to the patient. Additionally, this will avoid injury to the patient. There are IMUs in the device to track its movements through space.

A master-follower controller setup is used for the device. The operator remotely moves the controller through free space. The follower moves through the same path as the master. The master's movements are resisted proportionately to the force experienced at the end effector. The movement of both the master and the follower stops when the set maximum force value is exceeded.

4. Human Interface Design

The intended population of the device is for women who may be at risk of cervical cancer [4]. This population will primarily be women between the ages of 25 and 69. As this device is used for a sensitive procedure, training device operators is of high importance to the patient experience. The operator of this device must be a medical professional who has previously undergone training on performing a traditional pap smear. Before using the device, they must spend time operating the device through its full workspace in an open environment where they can receive visual feedback. While this visual feedback will not be available during actual pelvic exams, its use in training will help the operator to build relevant proprioception. The operator should be able to explain the type of motion and range of motion at each joint. At this time, they should also be informed of the force range the device is capable of imparting and demonstrate knowledge of appropriate force ranges for pap smears. Before moving onto a patient, they should practice on a pelvic exam simulator mannequin. They should also be advised to brief patients on what to expect relative to past experiences while undergoing the pap smear.

Prior testing of the device should occur on a pelvic exam simulator mannequin with a laparoscopic camera providing visual feedback. Subsequent testing with human subjects should also occur before the device is used on patients. In these tests, the subjects should be asked to give live verbal feedback on their physical experience. After testing, the subjects should also be asked further about their experiences with the device. The information gained through this process will not only serve to evaluate the device's performance but further inform how device operators are trained.

5. Mathematical Analyses

5.1. Forward Kinematics

The robot end-effector position can be calculated from its joint angles using forward kinematics. After drawing up the kinematic diagram, the Denavit-Hartenberg (DH) parameters were formulated. Next, subsequent transformations were computed for the three spherical joints and the prismatic joint, respectively. Finally, the matrices were processed in MATLAB to give the resultant transformation*.

5.2. Jacobian Matrix

The transformation matrices computed earlier were utilized to calculate the linear and angular velocity jacobian. This would allow for the robot joint velocities to be determined from its workspace velocities*.

***Note:** Due to the large entries of the final transformation matrix and the jacobian matrix, the result was not displayed in the report. Instead, the MATLAB file, 'robotkinematics.m' contains both outputs.*

5.3. Manipulable Workspace

Shown below is the robot with its manipulable workspace in blue. The workspace is spherical as all joints are able to pass through each other and the ground. The actual robot model in the plot is the Kinova gen3, which was imported from MATLAB's robotics systems toolbox. This robot was chosen as it most closely resembles our design and features the same functionality.

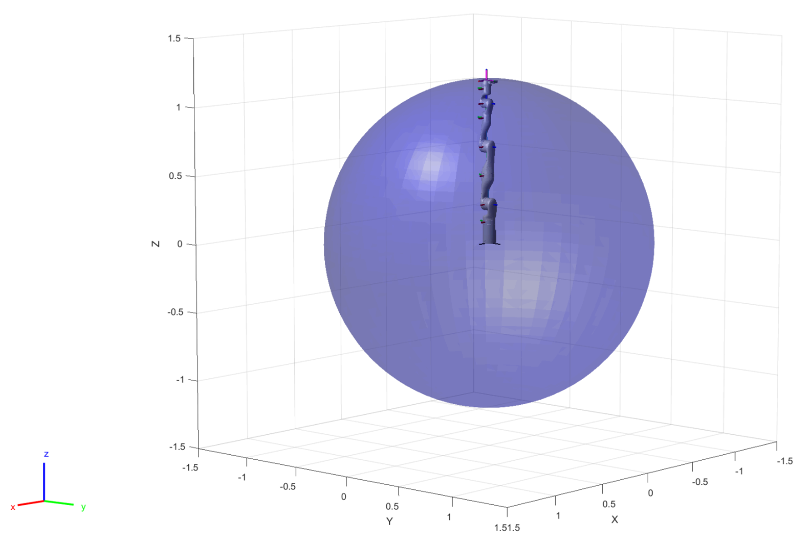


***Figure 2:** The robot manipulator in its home position, with the workspace plotted in blue.*

6. Conclusion

In conclusion, cervical cancer remains a significant public health concern worldwide, and regular screenings are essential to detect and treat the disease early. However, the current Pap smear procedure can be uncomfortable and challenging for many women, leading to delays or avoidance of these vital checkups. Our team's innovative solution, a robot manipulator for conducting Pap smear tests, offers a promising alternative that can significantly improve patient comfort, increase accessibility, and enhance accuracy. With the potential to save time for healthcare professionals and patients, this autonomous approach can increase checkup rates, reduce mortality rates, and ultimately contribute to better healthcare outcomes for women in Canada and beyond.

7. References

[1].NCI Dictionary of Cancer Terms. National Cancer Institute. (n.d.). Retrieved from https://www.cancer.gov/publications/dictionaries/cancer-terms/def/pap-smear

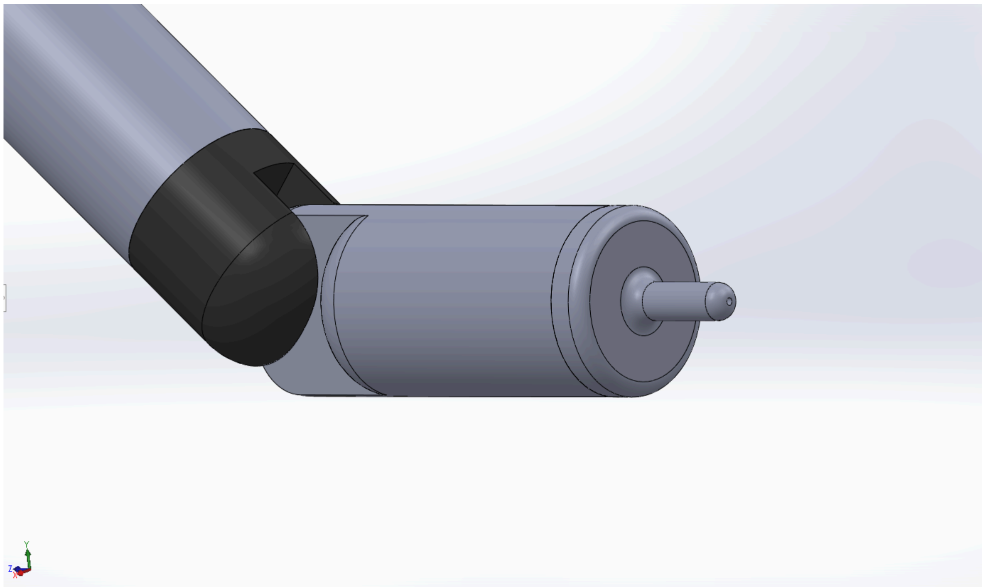
[2]. Wright, T. (2023, January 16). Cervical Cancer Rates in Canada and U.S. are Dropping. Experts Think They Know Why - National. Global News. Retrieved from https://globalnews.ca/news/9414113/cervical-cancer-canada-us-dropping-hpv-vaccine-experts/#:~:text=In%20Canada%2C%20an%20estimated%201%2C450,to%20Canadian%20Cancer%20Society%20data

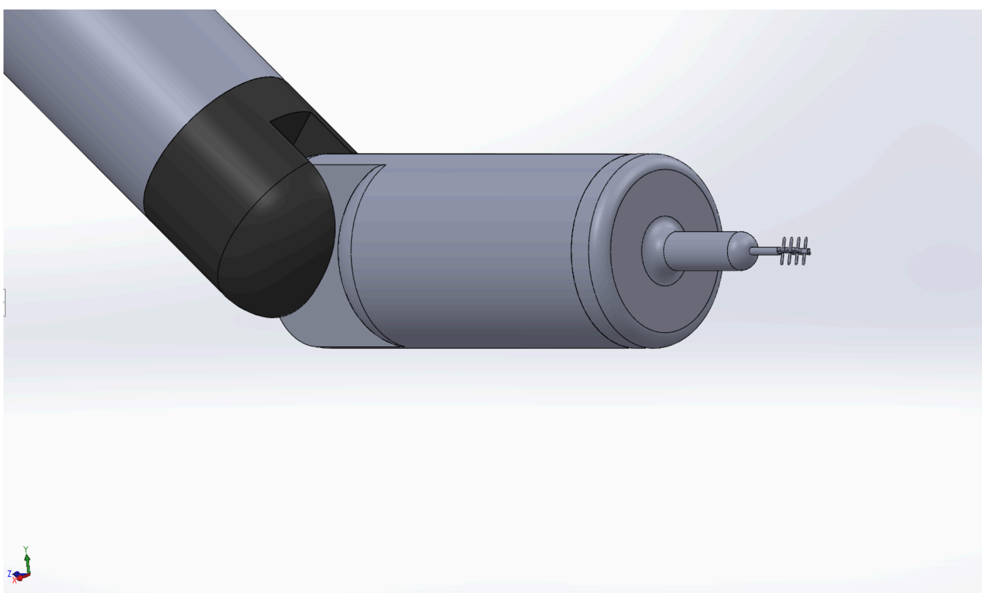
[3]. Pap test. Pap Test | Johns Hopkins Medicine. (2019, August 14). Retrieved from https://www.hopkinsmedicine.org/health/treatment-tests-and-therapies/pap-test#:~:text=Your%20healthcare%20provider%20will%20use,for%20this%20test%20as%20well

[4]. Get Screened [Internet]. Get Screened. Retrieved from http://www.bccancer.bc.ca/screening/cervix/get-screened#:~:text=Cervix%20screening%20(Pap%20test)%20can,cervical%20cancer%20every%20three%20years.

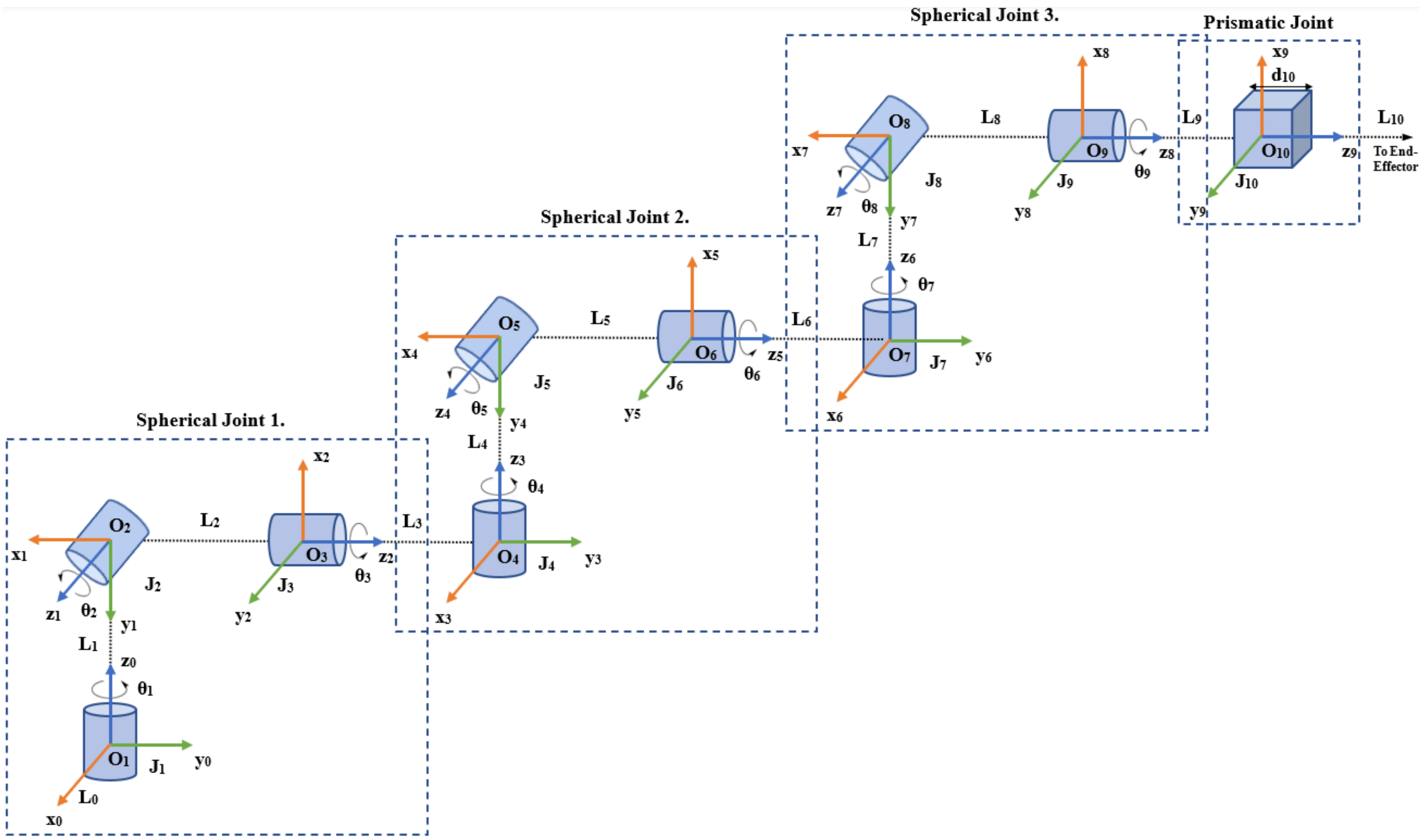
8. Appendix

Appendix A: SolidWorks Sketches (CAD)





Appendix B: Forward Kinematics (Diagram, DH Parameters, Transformation Matrices, Code)



Denavit-Hartenberg (DH) Parameters Table					
Joint	Link	a_i	α_i	d_i	θ_i
Spherical Joint 1,	1.	0	−90°	d_1	θ_1^*
	2.	0	90°	0	θ_2^*
	3.	0	90°	d_3	θ_3^*
Spherical Joint 2.	4.	0	−90°	d_4	θ_4^*
	5.	0	90°	0	θ_5^*
	6.	0	90°	d_6	θ_6^*
Spherical Joint 3.	7.	0	−90°	d_7	θ_7^*
	8.	0	90°	0	θ_8^*
	9.	0	0	d_9	θ_9^*
Prismatic Joint	10.	0	0	d_{10}^*	0
** variable*					

Transformation Matrix of Spherical Joint 1.

$$
{}^{0}\mathbf{T}_1 = \begin{bmatrix} c_{\theta_1} & -s_{\theta_1}c_{\alpha_1} & s_{\theta_1}s_{\alpha_1} & a_1c_{\theta_1} \\ s_{\theta_1} & c_{\theta_1}c_{\alpha_1} & -c_{\theta_1}s_{\alpha_1} & a_1s_{\theta_1} \\ 0 & s_{\alpha_1} & c_{\alpha_1} & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_1 & 0 & -s_1 & 0 \\ s_1 & 0 & c_1 & 0 \\ 0 & -1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{1}\mathbf{T}_2 = \begin{bmatrix} c_{\theta_2} & -s_{\theta_2}c_{\alpha_2} & s_{\theta_2}s_{\alpha_2} & a_2c_{\theta_2} \\ s_{\theta_2} & c_{\theta_2}c_{\alpha_2} & -c_{\theta_2}s_{\alpha_2} & a_2s_{\theta_2} \\ 0 & s_{\alpha_2} & c_{\alpha_2} & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_2 & 0 & s_2 & 0 \\ s_2 & 0 & -c_2 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{2}\mathbf{T}_3 = \begin{bmatrix} c_{\theta_3} & -s_{\theta_3}c_{\alpha_3} & s_{\theta_3}s_{\alpha_3} & a_3c_{\theta_3} \\ s_{\theta_3} & c_{\theta_3}c_{\alpha_3} & -c_{\theta_3}s_{\alpha_3} & a_3s_{\theta_3} \\ 0 & s_{\alpha_3} & c_{\alpha_3} & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_3 & 0 & s_3 & 0 \\ s_3 & 0 & -c_3 & 0 \\ 0 & 1 & 0 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Transformation Matrix of Spherical Joint 2.

$$
{}^{3}\mathbf{T}_4 = \begin{bmatrix} c_{\theta_4} & -s_{\theta_4}c_{\alpha_4} & s_{\theta_4}s_{\alpha_4} & a_4c_{\theta_4} \\ s_{\theta_4} & c_{\theta_4}c_{\alpha_4} & -c_{\theta_4}s_{\alpha_4} & a_4s_{\theta_4} \\ 0 & s_{\alpha_4} & c_{\alpha_4} & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_4 & 0 & -s_4 & 0 \\ s_4 & 0 & c_4 & 0 \\ 0 & -1 & 0 & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{4}\mathbf{D}_5 = \begin{bmatrix} c_{\theta_5} & -s_{\theta_5}c_{\alpha_5} & s_{\theta_5}s_{\alpha_5} & a_5c_{\theta_5} \\ s_{\theta_5} & c_{\theta_5}c_{\alpha_5} & -c_{\theta_5}s_{\alpha_5} & a_5s_{\theta_5} \\ 0 & s_{\alpha_5} & c_{\alpha_5} & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_5 & 0 & s_5 & 0 \\ s_5 & 0 & -c_5 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{5}\mathbf{D}_6 = \begin{bmatrix} c_{\theta_6} & -s_{\theta_6}c_{\alpha_6} & s_{\theta_6}s_{\alpha_6} & a_6c_{\theta_6} \\ s_{\theta_6} & c_{\theta_6}c_{\alpha_6} & -c_{\theta_6}s_{\alpha_6} & a_6s_{\theta_6} \\ 0 & s_{\alpha_6} & c_{\alpha_6} & d_6 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_6 & 0 & s_6 & 0 \\ s_6 & 0 & -c_6 & 0 \\ 0 & 1 & 0 & d_6 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Transformation Matrix of Spherical Joint 3.

$$
{}^{6}\mathbf{T}_7 = \begin{bmatrix} c_{\theta_7} & -s_{\theta_7}c_{\alpha_7} & s_{\theta_7}s_{\alpha_7} & a_7c_{\theta_7} \\ s_{\theta_7} & c_{\theta_7}c_{\alpha_7} & -c_{\theta_7}s_{\alpha_7} & a_7s_{\theta_7} \\ 0 & s_{\alpha_7} & c_{\alpha_7} & d_7 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_7 & 0 & -s_7 & 0 \\ s_7 & 0 & c_7 & 0 \\ 0 & -1 & 0 & d_7 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{7}\mathbf{T}_8 = \begin{bmatrix} c_{\theta_8} & -s_{\theta_8}c_{\alpha_8} & s_{\theta_8}s_{\alpha_8} & a_8c_{\theta_8} \\ s_{\theta_8} & c_{\theta_8}c_{\alpha_8} & -c_{\theta_8}s_{\alpha_8} & a_8s_{\theta_8} \\ 0 & s_{\alpha_8} & c_{\alpha_8} & d_8 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_8 & 0 & s_8 & 0 \\ s_8 & 0 & -c_8 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{8}\mathbf{T}_9 = \begin{bmatrix} c_{\theta_9} & -s_{\theta_9}c_{\alpha_9} & s_{\theta_9}s_{\alpha_9} & a_9c_{\theta_9} \\ s_{\theta_9} & c_{\theta_9}c_{\alpha_9} & -c_{\theta_9}s_{\alpha_9} & a_9s_{\theta_9} \\ 0 & s_{\alpha_9} & c_{\alpha_9} & d_9 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_9 & -s_9 & 0 & 0 \\ s_9 & c_9 & 0 & 0 \\ 0 & 0 & 1 & d_9 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Transformation Matrix of the Prismatic Joint.

$$
{}^{9}\mathbf{T}_{10} = \begin{bmatrix} c_{\theta_{10}} & -s_{\theta_{10}}c_{\alpha_{10}} & s_{\theta_{10}}s_{\alpha_{10}} & a_{10}c_{\theta_{10}} \\ s_{\theta_{10}} & c_{\theta_{10}}c_{\alpha_{10}} & -c_{\theta_{10}}s_{\alpha_{10}} & a_{10}s_{\theta_{10}} \\ 0 & s_{\alpha_{10}} & c_{\alpha_{10}} & d_{10} \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_{10} \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$