RBE 500 Homework #3

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Problem 4.2

Verify Equation (4.7) by direct calculation.

$$S(a)p = a \times p \tag{4.7}$$

Solution

Suppose the vectors a and p are given as

$$a = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}, p = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix}$$

By the definition of the cross-product, we know

$$a \times p = \begin{bmatrix} a_2p_3 - a_3p_2 \\ a_3p_1 - a_1p_3 \\ a_1p_2 - a_2p_1 \end{bmatrix} \tag{1}$$

Also, by the definition of skew-symmetric matrices, we know the form of $S(a)$, where a is the vector we have already defined,

$$S(a) = \begin{bmatrix} 0 & -a_z & a_y \\ a_z & 0 & -a_x \\ -a_y & a_x & 0 \end{bmatrix}$$

Hence, by normal matrix multiplication,

$$S(a)p = \begin{bmatrix} 0 - a_3p_2 + a_2p_3 \\ a_3p_1 + 0 - a_1p_3 \\ -a_2p_1 + a_1p_2 + 0 \end{bmatrix} = \begin{bmatrix} a_2p_3 - a_3p_2 \\ a_3p_1 - a_1p_3 \\ a_1p_2 - a_2p_1 \end{bmatrix}$$

Which is the same as (1). Therefore, Equation (4.7) is proved.

Problem 4.3

Prove the assertion given in Equation (4.9) that $R(a \times b) = Ra \times Rb$ for $R \in SO(3)$.

Solution

Let $v = R(a \times b)$, and $u = Ra \times Rb$. If v and u are the to be proved as the same vector, then it must be shown that they have the exact same magnitude and direction. Let us consider magnitude and direction of v and u separately.

Magnitude

Since $R \in SO(3)$, $\det R = 1$, which means that the linear transformation R does not change the length (norm) of any vector that it transforms (rotates). Hence we can say

$$\|R(a \times b)\| = \|a \times b\| \tag{1}$$
$$\|Ra\| = \|a\| \tag{2}$$
$$\|Rb\| = \|b\| \tag{3}$$

Using the definition of the cross product along with (1), we can state that

$$\|v\| = \|R(a \times b)\| = \|a \times b\| = \|a\|\|b\| \sin\theta \tag{4}$$

Again using the definition of the cross product along with (2) and (3), we can state that

$$\|u\| = \|Ra \times Rb\| = \|Ra\|\|Rb\| \sin\theta = \|a\|\|b\| \sin\theta \tag{5}$$

We can see that (4) and (5) are equal. Therefore,

$$\|v\| = \|u\|$$

Which means that the magnitude of v and u are the same.

Direction

Since $R \in SO(3)$ is a merely a rotational transformation of the 3 dimensional vector space, any directional relationships given by the right-hand curl rule before R has been applied must remain preserved and obtainable by the right-hand curl rule even after R has been applied.

Now, let us assume that the vectors a and b lie in the plane P. Also, assume $a \times b$ lies in the direction gvien by $\hat{q}$. We know that $\hat{q}$ can be obtained by applying the right-hand curl rule from a to b.

After R is applied, P becomes plane P_R, and $\hat{q}$ becomes $\hat{q_R}$. This means that $v = R(a \times b)$ lies along $\hat{q_R}$. Also, vector a and b become vectors Ra and Rb, which now lie in plane P_R. However, we can still obtain $\hat{q_R}$ by applying the right-hand curl rule from Ra to Rb, since this relationship is preserved. Hence, $u = Ra \times Rb$ lies in the direction $\hat{q_R}$. Therefore, v and u lie in the same direction.

Since v and u lie in the same direction and have the same magnitude, they are the same vector. Hence, (4.9) is proved.

Problem 4.5

Suppose that a = (1,-1,2) and that $R = R_{x,90}$. Show by direct calculation that $RS(a)R^T = S(Ra)$.

Solution

$$R = R_{x,90} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(90) & -\sin(90) \\ 0 & \sin(90) & \cos(90) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix}$$

$$S(a) = \begin{bmatrix} 0 & -2 & -1 \\ 2 & 0 & -1 \\ 1 & 1 & 0 \end{bmatrix}$$

$$\begin{aligned} RS(a)R^T &= \left(\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & -2 & -1 \\ 2 & 0 & -1 \\ 1 & 1 & 0 \end{bmatrix} \right) \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{bmatrix} \\ &= \begin{bmatrix} 0 & -2 & -1 \\ -1 & -1 & 0 \\ 2 & 0 & -1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{bmatrix} \\ &= \begin{bmatrix} 0 & 1 & -2 \\ -1 & 0 & -1 \\ 2 & 1 & 0 \end{bmatrix} \end{aligned}$$

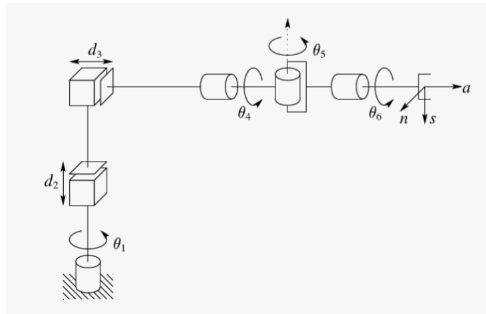
$$Ra = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ -1 \\ 2 \end{bmatrix} = \begin{bmatrix} 1 \\ -2 \\ -1 \end{bmatrix}$$

$$S(Ra) = \begin{bmatrix} 0 & 1 & -2 \\ -1 & 0 & -1 \\ 2 & 1 & 0 \end{bmatrix}$$

As we can see, it has been shown that $RS(a)R^T = S(Ra)$.

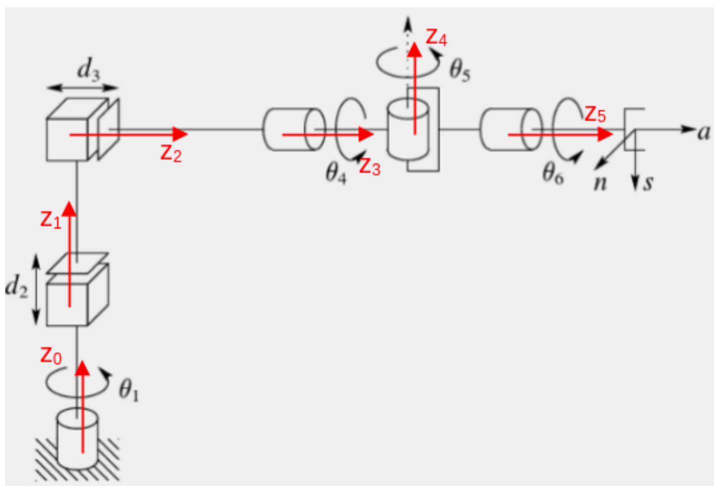
Jacobian Problem

Derive the Jacobian for the following image.



Solution

For easy visualization, let us draw the z axes for each joint.



We can see that we have 6 joints, so $n = 6$. Let us also form the table given in the lecture videos:

	Linear component	Angular component
Revolute joint	$J_{v_i} = z_{i-1}^0 \times (o_n^0 - o_{i-1}^0)$	$J_{v_i} = z_{i-1}^0$
Prismatic joint	$J_{\omega_i} = z_{i-1}^0$	$J_{\omega_i} = 0$

Using this table, and the fact that the upper half of the Jacobian contains linear components while the bottom half contains angular components, we have

$$J = \begin{bmatrix} z_0 \times (o_6 - o_0) & z_1 & z_2 & z_3 \times (o_6 - o_3) & z_4 \times (o_6 - o_4) & z_5 \times (o_6 - o_5) \\ z_0 & 0 & 0 & z_3 & z_4 & z_5 \end{bmatrix}$$

Let us now describe how each of the z and o vectors can be obtained.

z_0 is simply the unit vector in the z-direction in the base frame, so, $z_0 = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T$.

Similarly, o_0 is the origin of the base frame, so it is given by $o_0 = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}^T$

o_6 can be obtained by using the $T_n^0 = A_0 \ldots A_n$ matrix (set $n = 6$) as part of forward kinematics, where matrices A_i are chosen using the Denavit-Hartenberg convention. Once the T (4×4) matrix is obtained, the o_n vector is simply the 3×1 matrix in the top-right corner of T. Similarly, we can obtain o_3, o_4, and o_5 by setting $n = 4, 5, 6$ for T_n^0.

By using $T_n^0 = A_0 \ldots A_n$ again we can obtain z_1, z_2, z_3, z_4, and z_5. The top-left 3×3 portion of the T_n^0 matrix is the R_n^0 matrix, for which each column is a basis vector. The right-most basis vector is the z_n vector.

Therefore, by using forward kinematics we can obtain each of our z and o vectors.

Report for ROS2 Portion

For this week's ROS assignment portion, I created a subscriber just like how we did for last week's assignment. I also used the same ros2 command type as the one last week, specifically, `ros2 topic pub --once ... <topic_name> <data_type> <data>`.

Futhermore, this week I set up my subscriber to accept 3 joint variable values from the publisher. These 3 values are floats that represent the angles for the three revolute joints $(\theta_1, \theta_2, \theta_3)$ of the robot manipulator we considered in Problem 3.5 of Homework #2. Using $\theta_1, \theta_2, \theta_3$, my subscriber calculated forward kinematics using the symbolic T matrix I calculated last week, given by

$$T_3^0 = \begin{bmatrix} c_1\,c_2\,c_3 - c_1\,s_2\,s_3 & -c_1\,c_2\,s_3 - c_1\,c_3\,s_2 & -s_1 & a_2\,c_1\,c_2 - a_3\,c_1\,s_2\,s_3 + a_3\,c_1\,c_2\,c_3 \\ c_2\,c_3\,s_1 - s_1\,s_2\,s_3 & -c_2\,s_1\,s_3 - c_3\,s_1\,s_2 & c_1 & a_2\,c_2\,s_1 - a_3\,s_1\,s_2\,s_3 + a_3\,c_2\,c_3\,s_1 \\ -c_2\,s_3 - c_3\,s_2 & s_2\,s_3 - c_2\,c_3 & 0 & d_1 - a_2\,s_2 - a_3\,c_2\,s_3 - a_3\,c_3\,s_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

I imported the `numpy` python package to put this T_3^0 matrix in a `numpy.array`, and then I printed the matrix for the given joint variables. In my code, I made sure to name c_i and s_i exactly that way so that I could visually verify any issues in setting up the matrix. The `math.cos` and `math.sin` python functions were used to for assigning values to c_i and s_i. I also set d_1, a_2, a_3 as 1 to make sure I could easily verify that my code is working correctly.