

$${}^0_{org}T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(q_0) & -\sin(q_0) & L_0 \cos(q_0) \\ 0 & \sin(q_0) & \cos(q_0) & L_0 \sin(q_0) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$${}^1_0T = \begin{bmatrix} \cos(q_1) & -\sin(q_1) & 0 & -L_1 \sin(q_1) \\ \sin(q_1) & \cos(q_1) & 0 & L_1 \cos(q_1) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$${}^2_1T = \begin{bmatrix} \cos(q_2) & -\sin(q_2) & 0 & -L_2 \sin(q_2) \\ \sin(q_2) & \cos(q_2) & 0 & L_2 \cos(q_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$${}^3_2T = \begin{bmatrix} \cos(q_3) & -\sin(q_3) & 0 & -L_3 \sin(q_3) \\ \sin(q_3) & \cos(q_3) & 0 & L_3 \cos(q_3) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$com_0 = \begin{bmatrix} 0 \\ l_0 \cos(q_0) \\ l_0 \sin(q_0) \\ 1 \end{bmatrix} \quad (5)$$

$$com_1 = \begin{bmatrix} -l_1 \sin(q_1) \\ l_1 \cos(q_1) \\ 0 \\ 1 \end{bmatrix} \quad (6)$$

$$com_2 = \begin{bmatrix} -l_2 \sin(q_2) \\ l_2 \cos(q_2) \\ 0 \\ 1 \end{bmatrix} \quad (7)$$

$$com_3 = \begin{bmatrix} -l_3 \sin(q_3) \\ l_3 \cos(q_3) \\ 0 \\ 1 \end{bmatrix} \quad (8)$$

$$x_{ee} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \quad (9)$$

$${}^1_{org}T = {}^0_{org}T {}^1_0T \quad (10)$$

$${}^2_{org}T = {}^0_{org}T {}^1_0T {}^2_1T \quad (11)$$

$${}^3_{org}T = {}^0_{org}T {}^1_0T {}^2_1T {}^3_2T \quad (12)$$

$$Jacobian = \begin{bmatrix} \frac{\partial x}{\partial q_0} & \frac{\partial x}{\partial q_1} & \frac{\partial x}{\partial q_2} & \frac{\partial x}{\partial q_3} \\ \frac{\partial y}{\partial q_0} & \frac{\partial y}{\partial q_1} & \frac{\partial y}{\partial q_2} & \frac{\partial y}{\partial q_3} \\ \frac{\partial z}{\partial q_0} & \frac{\partial z}{\partial q_1} & \frac{\partial z}{\partial q_2} & \frac{\partial z}{\partial q_3} \\ \frac{\partial \omega_x}{\partial q_0} & \frac{\partial \omega_x}{\partial q_1} & \frac{\partial \omega_x}{\partial q_2} & \frac{\partial \omega_x}{\partial q_3} \\ \frac{\partial \omega_y}{\partial q_0} & \frac{\partial \omega_y}{\partial q_1} & \frac{\partial \omega_y}{\partial q_2} & \frac{\partial \omega_y}{\partial q_3} \\ \frac{\partial \omega_z}{\partial q_0} & \frac{\partial \omega_z}{\partial q_1} & \frac{\partial \omega_z}{\partial q_2} & \frac{\partial \omega_z}{\partial q_3} \end{bmatrix} \quad (13)$$

$$J_0 = Jacobian(com_0) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -l_0 \sin(q_0) & 0 & 0 & 0 \\ l_0 \cos(q_0) & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (14)$$

$$J_1 = Jacobian({}^0_{org}T com_1) = \begin{bmatrix} 0 & -l_1 \cos(q_1) & 0 & 0 \\ -(L_0+l_1 \cos(q_1)) \sin(q_0) & -l_1 \sin(q_1) \cos(q_0) & 0 & 0 \\ (L_0+l_1 \cos(q_1)) \cos(q_0) & -l_1 \sin(q_0) \sin(q_1) & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad (15)$$

$$J_2 = Jacobian({}^1_{org}T com_2) \quad (16)$$

$$J_3 = Jacobian({}^2_{org}T com_3) \quad (17)$$

$$J_{EE} = Jacobian({}^3_{org}T x_{ee}) \quad (18)$$