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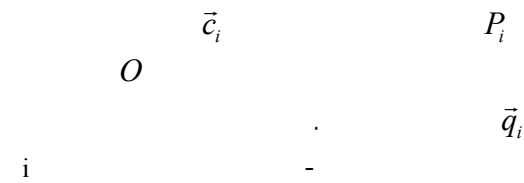
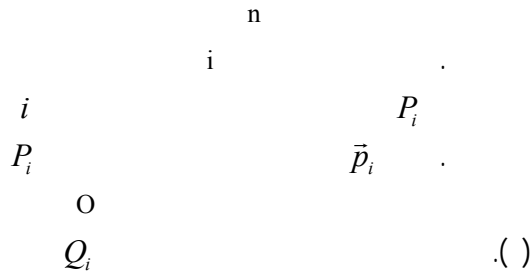
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$${}_q \vec{f}_i = \vec{f}_{ii} + m_i \vec{g} = m_i \vec{q}_i \quad (.)$$

$${}_q \vec{n}_i = \vec{n}_{ii} - \vec{c}_i \times \vec{f}_{ii} = {}_q \vec{I}_i \vec{\omega}_i + \vec{\omega}_i \times ({}_q \vec{I}_i \vec{\omega}_i) \quad (.)$$

$$q \quad i \quad : \vec{f}_i$$

$$i \quad : \vec{n}_i$$

$$j \quad i \quad : \vec{f}_{ij} \quad []$$

$$j \quad i \quad : \vec{n}_{ij} \quad []$$

$$i \quad : m_i$$

$$: {}_q \vec{I}_i$$

$$: \vec{\omega}_i$$

$$\vec{g} = [0, 0, -9.8] (m / \text{sec}^2) \quad : \vec{g}$$

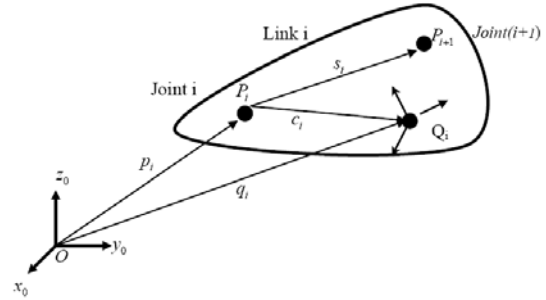
$$\vec{q}_i \quad \vec{c}_i$$

$$\vec{p}_i \quad i \quad i$$

$$\ddot{\vec{q}}_i = \ddot{\vec{p}}_i + \ddot{\vec{\omega}}_i \times \vec{c}_i + \vec{\omega}_i \times (\vec{\omega}_i \times \vec{c}_i) \quad ()$$

$$: \quad () \quad ()$$

$$\vec{f}_{ii} = m_i(\ddot{\vec{p}}_i - \vec{g}) + \ddot{\vec{\omega}}_i \times m_i \vec{c}_i + \vec{\omega}_i \times (\vec{\omega}_i \times m_i \vec{c}_i) \quad ()$$



$$\vec{c}_i \times (\vec{\omega}_i \times (\vec{\omega}_i \times \vec{c}_i)) \quad \vec{c}_i \times (\ddot{\vec{\omega}}_i \times \vec{c}_i)$$

\vec{c}_i
 i

$${}^p \vec{I}_i \quad p$$

$${}^q \vec{I}_i$$

$$\vec{n}_{ii} = (\vec{g} - \ddot{\vec{p}}_i) \times m_i \vec{c}_i + {}^p \vec{I}_i \ddot{\vec{\omega}}_i + \vec{\omega}_i \times ({}^p \vec{I}_i \vec{\omega}_i) \quad ()$$

$$\vec{\omega} \times \vec{c} = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix} \begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} \stackrel{\Delta}{=} [\vec{\omega} \times] \vec{c} \quad ()$$

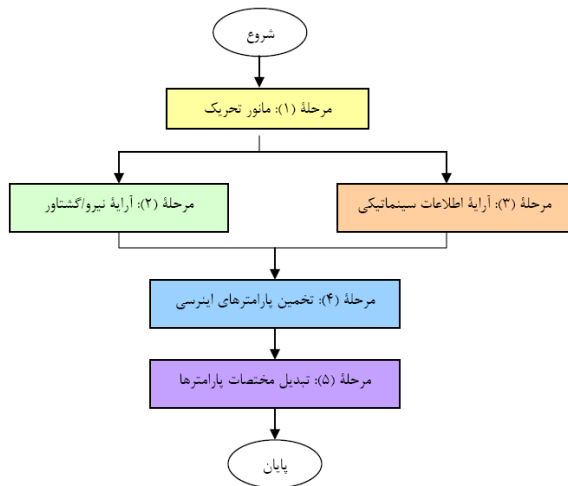
$$\vec{I} \vec{\omega} = \begin{bmatrix} \omega_x & \omega_y & \omega_z & 0 & 0 & 0 \\ 0 & \omega_x & 0 & \omega_y & \omega_z & 0 \\ 0 & 0 & \omega_x & 0 & \omega_y & \omega_z \end{bmatrix}_{3 \times 6} \begin{bmatrix} I_{xx} \\ I_{xy} \\ I_{xz} \\ I_{yy} \\ I_{yz} \\ I_{zz} \end{bmatrix}_{6 \times 1} \stackrel{\Delta}{=} [\cdot \vec{\omega}] \begin{bmatrix} I_{xx} \\ I_{xy} \\ I_{xz} \\ I_{yy} \\ I_{yz} \\ I_{zz} \end{bmatrix} \quad ()$$

$$\begin{bmatrix} \vec{f}_{ii} \\ \vec{n}_{ii} \end{bmatrix}_{6 \times 1} = \begin{bmatrix} \ddot{\vec{p}}_i - \vec{g} & [\ddot{\vec{\omega}}_i \times] + [\vec{\omega}_i \times][\vec{\omega}_i \times] & 0 \\ 0 & [(\vec{g} - \ddot{\vec{p}}_i) \times] & [\cdot \vec{\omega}_i] + [\vec{\omega}_i \times][\cdot \vec{\omega}_i] \end{bmatrix}_{6 \times 10} \begin{bmatrix} m_i \\ m_i \vec{c}_i \\ I_{xx_i} \\ I_{xy_i} \\ I_{xz_i} \\ I_{yy_i} \\ I_{yz_i} \\ I_{zz_i} \end{bmatrix} \quad ()$$

$$w_{ii_{6 \times 1}} = A_{i_{6 \times 10}} \phi_{i_{10 \times 1}} \quad ()$$

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$$\ddot{q} \quad \dot{q} \quad q$$

$$q_i(t) = \begin{cases} q_{iini} + \frac{1}{2} k_i t^2 \dots \dots \dots (0 < t < t_{bi}) \\ \frac{1}{2} k_i t_{bi}^2 + k_i t_{bi} (t - t_{bi}) \dots \dots \dots (t_{bi} < t < t_f - t_{bi}) \\ q_{ifinal} - \frac{1}{2} k_i (t - t_f)^2 \dots \dots \dots (t_f - t_{bi} < t < t_f) \end{cases} \quad ()$$

()

$$[s] \quad i \quad t_{bi}$$

$$[s] \quad : \quad t_f$$

$$[rad] \quad i \quad : \quad q_{iini}$$

$$[rad] \quad i \quad : \quad q_{ifinal}$$

k_i : $[rad / s^2]$ i :
 $t = 5$ (sec)
 $T = 0.05$ (sec)

$$\phi_{n_{10 \times 1}} = \left(A^T_{10 \times 600} A_{600 \times 10} \right)^{-1}_{10 \times 10} A^T_{10 \times 600} w_{600 \times 1}$$

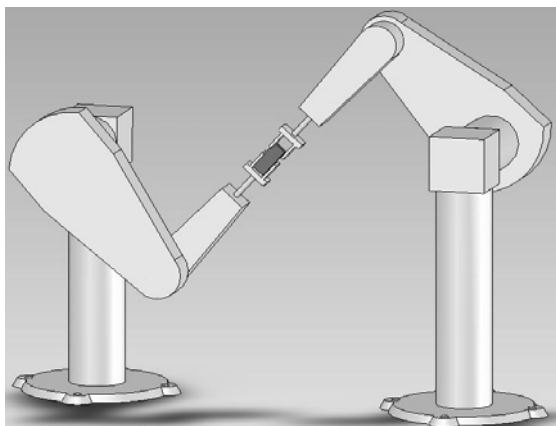
$(A^T A)$

SVD
 .[]

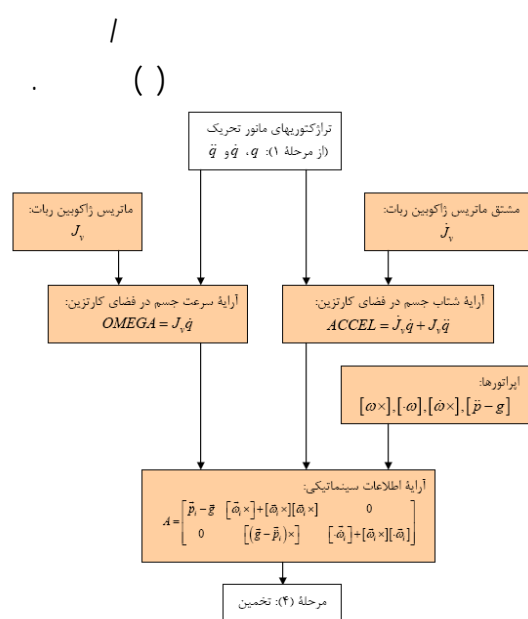
$$WRENCH = \begin{bmatrix} \vec{f}_{ii} \\ \vec{n}_{ii} \end{bmatrix} = - (J_v^T)^{-1} (\tau_o - \tau_m)$$

WRENCH

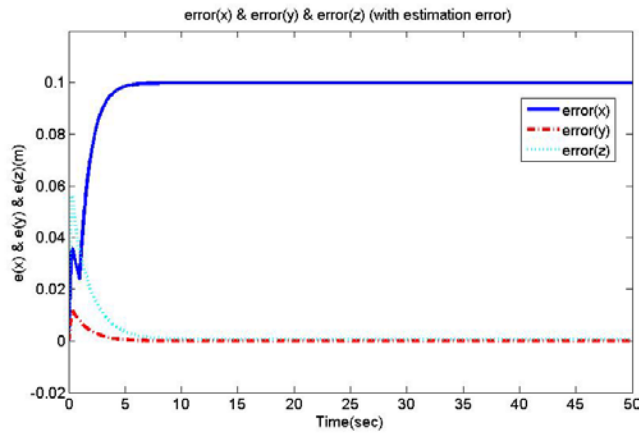
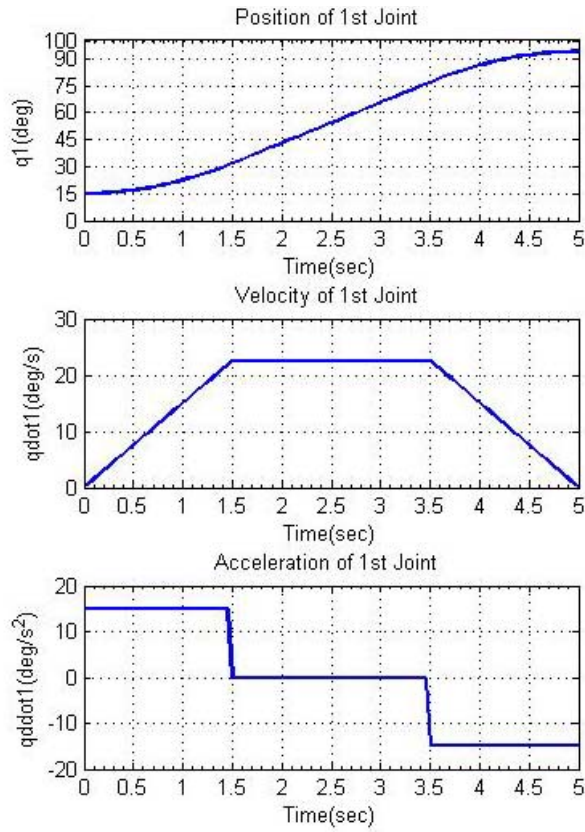
τ_o
 τ_m



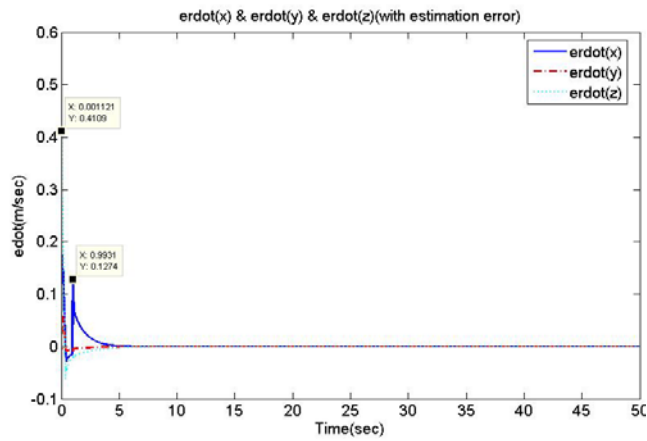
$[]$
 $12 \times 5 \times 2 [cm]$
 $m = 936 [gr]$



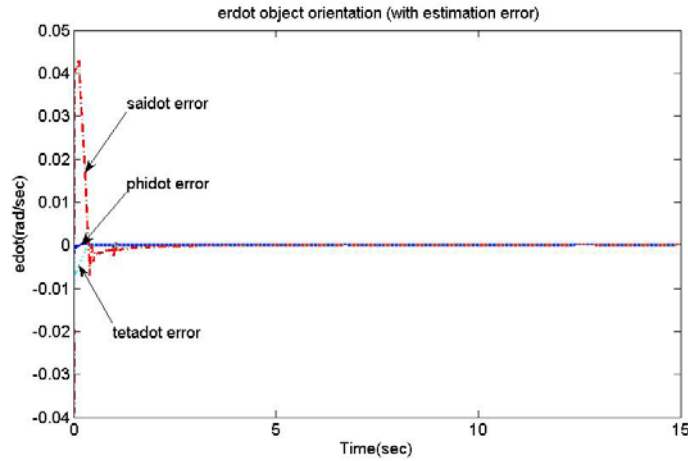
$$\begin{aligned}
 & \delta_E \\
 & C \\
 & \dot{x} \\
 & \dot{x} = J_c \dot{q} \quad () \\
 & J_c \\
 & t_b = 1.5 [s] \\
 & Q \\
 & Q = Q_{app} + Q_{react} \quad () \\
 & Q_{react} \\
 & Q_{app} \\
 & I_{xx} = 0.0011544 [kg.m^2], I_{yy} = 0.0002262 [kg.m^2] \quad () \\
 & I_{zz} = 0.0013182 [kg.m^2] \quad () \\
 & k = [0.262 \quad 0.001 \quad 0.11 \quad 0.715 \quad 0.01 \quad 0.5] (rad/s^2) \quad () \\
 & q_{ini} = [15 \quad 15 \quad 0 \quad -100 \quad 0 \quad 0] (deg) \quad () \\
 & q_{final} = [95 \quad 15.3 \quad 33 \quad 105 \quad 3 \quad 150] (deg) \quad () \\
 & -5.67\% \\
 & Q_{app} = Q_m + Q_f \quad () \\
 & Q_m \\
 & Q_f \\
 & M\ddot{x} + F_\omega = F_c + F_o + GF_e \quad () \\
 & [] [] \\
 & M \\
 & \ddot{x} \\
 & x = [x_G^T, \delta_{obj}^T]^T \quad [] \\
 & x_G \\
 & \delta_{obj} \\
 & MIC \\
 & F_\omega \\
 & H(q)\ddot{x} + C(q, \dot{q}) = Q \quad () \\
 & q \\
 & F_c \\
 & F_o \\
 & x \\
 & x_E \\
 & x = [x_E^T, \delta_E^T]
 \end{aligned}$$



.() :



.() :



$$F_e = \begin{Bmatrix} F_e^{(1)} \\ F_e^{(2)} \end{Bmatrix} \quad ()$$

$$F_e^{(i)} = \begin{Bmatrix} f_e^{(i)} \\ n_e^{(i)} \end{Bmatrix}_{6 \times 1} \quad ()$$

$$M = \begin{bmatrix} M_{obj} 1_{3 \times 3} & \mathbf{0}_{3 \times 3} \\ \mathbf{0}_{3 \times 3} & S_{obj}^T \bar{I}_G S_{obj} \\ \bar{I}_G & M_{obj} \end{bmatrix} \quad ()$$

$$G = \begin{bmatrix} 1_{3 \times 3} & \mathbf{0}_{3 \times 3} & 1_{3 \times 3} & \mathbf{0}_{3 \times 3} \\ S_{obj}^T [r_e^{(1)}]_{3 \times 3}^\times & \mathbf{0}_{3 \times 3} & S_{obj}^T [r_e^{(2)}]_{3 \times 3}^\times & \mathbf{0}_{3 \times 3} \\ \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & 1_{3 \times 3} \end{bmatrix} \quad ()$$

$$F_\omega = \begin{Bmatrix} \mathbf{0}_{3 \times 1} \\ S_{obj}^T \left([\omega_{obj}]^\times \bar{I}_G \omega_{obj} + \bar{I}_G \dot{S}_{obj} \delta_{obj} \right) \end{Bmatrix} \quad ()$$

$$S_{obj} = \begin{bmatrix} 0 & -S\phi & C\phi S\theta \\ 0 & C\phi & S\phi S\theta \\ 1 & 0 & C\theta \end{bmatrix} \quad ()$$

$$F_c = \begin{Bmatrix} f_c \\ S_{obj}^T n_c \end{Bmatrix} \quad ()$$

$$x \quad x_w = 1[m]$$

$$F_o = \begin{Bmatrix} f_o \\ S_{obj}^T n_o \end{Bmatrix} \quad ()$$

$$k_w = 1e5[N/m]$$

$$f_o = m_{obj} g$$

$$n_o = 0$$

$$F_{e_{req}} = G^\# \left\{ \begin{array}{l} \hat{M} M_{des}^{-1} (M_{des} x_{des} + K_d \dot{e} + K_p e + \hat{F}_c) \\ + F_\omega - (\hat{F}_c + F_o) \end{array} \right\} \quad ()$$

\hat{M}

$$\begin{aligned} f_c &= k_w (x_w - (x_o + r_c)) \\ n_c &= r_c \times f_c \end{aligned} \quad ()$$

r_c

RCC

$$\begin{aligned} \tilde{Q}_m^{(i)} &= \tilde{H}^{(i)} (q^{(i)}) M_{des}^{-1} [M_{des} \ddot{x}_{des}^{(i)} + K_d \dot{e}^{(i)} + K_p e^{(i)} + \hat{F}_c] \\ + \tilde{C}^{(i)} (q^{(i)}, \dot{q}^{(i)}) \end{aligned} \quad ()$$

$$\begin{aligned} f_e^{(2)} &= k_e (x_e^{(2)} - (x_o + r_e^{(2)} + l_{free})) \\ + b_e (\dot{x}_e^{(2)} - (\dot{x}_o + r_e^{(2)})) \end{aligned} \quad ()$$

b_e k_e

$x_e^{(2)}$ *RCC* l_{free} *RCC*

0.2 [m]

RCC

RCC

0.1 [m]

$$b_e = 500 [N \cdot s / m] \quad k_e = 2000 [N / m]$$

MIC

$$\begin{aligned} M_{des} &= \text{diag}(10, 10, 10, 1, 1, 1) \\ K_p &= \text{diag}(200, 200, 200, 10, 10, 10) \\ K_d &= \text{diag}(300, 300, 300, 1000, 1000, 1000) \end{aligned} \quad ()$$

$$\begin{aligned} X_{Gides} &= 0.7 + 0.4(1 - e^{-t}) [m], Y_{Gides} = 0.2 [m] \\ Z_{Gides} &= 0.2(1 - e^{-t}) [m] \\ \theta_{xdes} = \theta_{ydes} = \theta_{zdes} &= 0.0 [rad] \end{aligned} \quad ()$$

$$f_e^{(i)} = B_1^{-1} \left\{ \begin{array}{l} \left[J_r^{(i)} \dot{q}^{(i)} + J_r^{(i)} \ddot{q}^{(i)} + \omega_{dy} \times (\omega_{dy} \times (-r_e^{(i)})) + (-r_e^{(i)}) \times \dot{\omega}_{dy} \right] \\ + (r_e^{(i)} \times I_o^{(-1)}) S_{obj}^T (I_o \dot{\omega}_{dy} + \omega_{dy} \times I_o \omega_{dy} - (n_c + n_o)) \\ - B_2 f_e^{(2)} - (f_c + f_o) \end{array} \right\} \quad ()$$

$$B_1 = (r_e^{(1)} \times I_o^{(-1)}) S_{obj}^T r_e^{(1)\times} + 1_{3 \times 3} \quad ()$$

$$B_2 = (r_e^{(1)} \times I_o^{(-1)}) S_{obj}^T r_e^{(2)\times} + 1_{3 \times 3}$$

$$\hat{F}_c = M \ddot{x} + F_\omega - F_o - GF_e \quad ()$$

$$\ddot{x} = \frac{\dot{x}_t - 2\dot{x}_{t-\Delta t} + \dot{x}_{t-2\Delta t}}{\Delta t^2} \quad ()$$

x

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 y

MIC

-5.67%

MIC

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واژه های انگلیسی به ترتیب استفاده در متن

- 1 - Multiple Impedance Control, MIC
 - 2 - Object Impedance Control
 - 3 - On-Line
 - 4 - Off-Line
 - 5 - Grasp Matrix
 - 6 - Gain
 - 7 - Contact
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