



Many on-orbit servicing operations call for gripping a service object. One of the problems to be solved in gripping an object is to slow down its rotation. Examples of well-known projects for solving this problem are given. Based on the familiar concept of a two-stage gripping scheme and on the familiar concepts of the cellular architecture of a spacecraft and a space robot, it is proposed that the cellular architecture concept be applied to the construction of a self-contained system for slowing down the rotation of a non-cooperative object of on-orbit servicing. The system is made up of informationally connected modules or cells of minimum necessary functionality fixed on a service object (solid body). The minimum necessary functionality includes accelerometer-based measurement of the linear accelerations at the points of attachment of the sensor cells to the body, applying forces to the object using actuators in the form of propulsion systems, and data exchange and processing to determine the actuator forces. This paper addresses the problem of developing algorithms of the operation of the system considered, namely, determining the angular motion parameters and the center of mass position from the accelerometer data and determining control actions to slow down the rotation of the object. The aim of this work is to demonstrate the feasibility of the proposed self-contained system. The problems of estimation of the angular motion parameters and the center of mass position, braking impulse generation, and estimation of the object inertia tensor were reduced to finding the best linear unbiased estimate, the normal pseudosolution of an underdetermined system of algebraic equations, and the solution of an overdetermined one. A numerical simulation of the operation of the self-contained system was conducted, and the simulation results confirmed the operability of the proposed algorithms and thus the principle feasibility of the proposed self-contained system. The proposed concept of the construction of a self-contained system for slowing down the rotation of an object of on-orbit servicing and the system operation algorithm developed may be used in the design of on-orbit servicing spacecraft.

**Keywords:** *on-orbit servicing, non-cooperative object, self-contained system for rotation slowing-down, operation algorithms, rotation characterization, control action generation.*

... ( ) ... [1], ... [2], 3°/ 30°/ ... CleanSpace One [3], ( ). ... [4], [5]. ( )

[6].

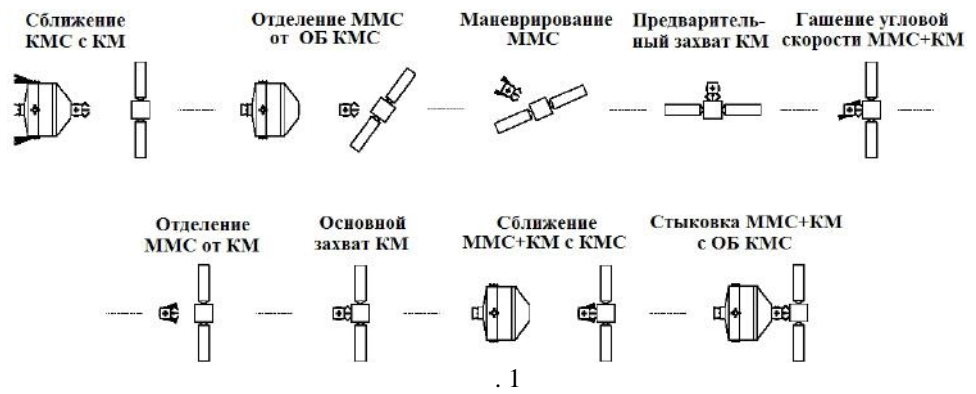
[7].

[8].

[9]

[8]

1.



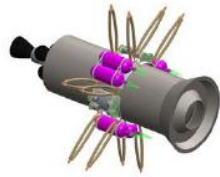
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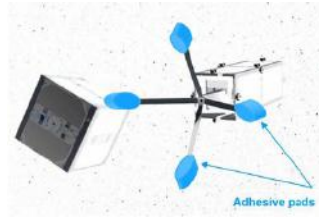


(.2).



.2

[1].



.3

3),



.4

[11]).

(Cellular Space Robot).

[13] (

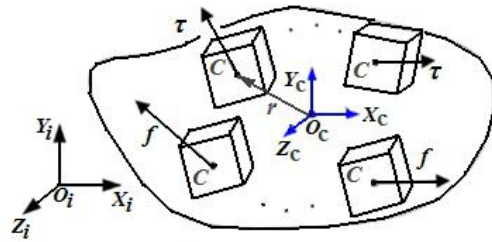
(gecko gripper),

[10], [11].

(.4,

[12],

- Brain -
- Actuator -
- Sensor -
- Communication -
- Power Management -



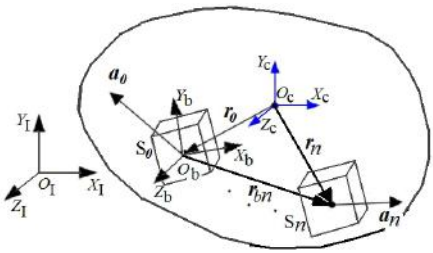
$$O_i X_i Y_i Z_i$$

$$O_c X_c Y_c Z_c$$

$$, C -$$

[12]

[12], [13].



[12].

$$O_I X_I Y_I Z_I \rightarrow O_c X_c Y_c Z_c \rightarrow O_b X_b Y_b Z_b$$

$$a_n = a_c + \dot{\omega} \times r_{sn} + \omega \times (\omega \times r_{sn})$$

$$a_n = a_c + \dot{\omega} \times r_n + \omega \times (\omega \times r_n), \quad a_c = F_e / m, \quad (1)$$

$$F_e = m a_c$$

$${}^b a_n = {}^b a_c + ({}^b \dot{\omega}^\times)({}^b r_n) + ({}^b \omega^\times)({}^b \omega^\times)({}^b r_n), \quad (2)$$

$${}^b a_n - {}^b a_0 = ({}^b \dot{\omega}^\times)({}^b r_{bn}) + ({}^b \omega^\times)({}^b \omega^\times)({}^b r_{bn}). \quad (3)$$

$$Dx = z, \quad D = [D_1^T \mid D_2^T \mid \dots \mid D_{N-1}^T]^T,$$

$$x = [x_1, x_2, x_3, x_4, x_5, x_6, \dot{\omega}_x, \dot{\omega}_y, \dot{\omega}_z]^T, \quad [\dot{\omega}_x \ \dot{\omega}_y \ \dot{\omega}_z]^T \equiv {}^b \dot{\omega} \quad (4)$$

$$x_1 = \omega_y \omega_z, \quad x_2 = \omega_z \omega_x, \quad x_3 = \omega_x \omega_y, \quad [\omega_x \ \omega_y \ \omega_z]^T \equiv {}^b \omega,$$

$$x_4 = \omega_y^2 + \omega_z^2, \quad x_5 = \omega_z^2 + \omega_x^2, \quad x_6 = \omega_x^2 + \omega_y^2,$$

:

$$z = [z_1^T \ z_2^T \ \dots \ z_{N-1}^T]^T, \quad z_i = ({}^b a_n - {}^b a_0),$$

D:

$$D_n = \begin{bmatrix} 0 & \zeta_n & \eta_n & -\xi_n & 0 & 0 & 0 & \zeta_n & -\eta_n \\ \zeta_n & 0 & \xi_n & 0 & -\eta_n & 0 & -\zeta_n & 0 & \xi_n \\ \eta_n & \xi_n & 0 & 0 & 0 & -\zeta_n & \eta_n & -\xi_n & 0 \end{bmatrix},$$

$$[\xi_n \ \eta_n \ \zeta_n]^T = {}^b r_{bn}, \quad n = 1, 2, \dots, N-1.$$

$$O_n X_n Y_n Z_n.$$

$n_0$

$${}^b a_n = {}^b A_n ({}^n a_n),$$

${}^b A_n$

$$O_n X_n Y_n Z_n \quad O_b X_b Y_b Z_b, \quad {}^n a_n$$

$$\hat{x} \quad x$$

$\tilde{P}$

$$\tilde{x} = x - \hat{x} \quad [14]$$

$$\hat{x} = (D^T S^{-1} D + P^{-1})^{-1} D^T S^{-1} z, \quad \tilde{P} = (D^T S^{-1} D + P^{-1})^{-1}, \quad (5)$$

P S

s.

x

(

$$P^{-1} = 0)$$

D

x, . . .

x,

(5)

$$\hat{x} = (D^T S^{-1} D)^{-1} D^T S^{-1} z, \quad \tilde{P} = (D^T S^{-1} D)^{-1}. \quad (6)$$

(6)

$$\hat{x} = (D^T D)^{-1} D^T z, \quad \tilde{P} = (D^T D)^{-1} D^T S D (D^T D)^{-1}. \quad (7)$$

$$\hat{x} \quad (4)$$

${}^b \hat{\omega}$

$$O_b X_b Y_b Z_b.$$

${}^b \hat{\omega}$

${}^b \omega$

$x_4, x_5, x_6$

x:

$$2\hat{\omega}_x^2 = (-\hat{x}_4 + \hat{x}_5 + \hat{x}_6), \quad 2\hat{\omega}_y^2 = (+\hat{x}_4 - \hat{x}_5 + \hat{x}_6), \quad 2\hat{\omega}_z^2 = (+\hat{x}_4 + \hat{x}_5 - \hat{x}_6), \quad (8)$$





$$\Phi(\dot{\omega}, \omega) p = 0,$$

$$\Phi(\dot{\omega}, \omega) = \begin{bmatrix} \dot{\omega}_x & -\omega_y \omega_z & \omega_y \omega_z & \dot{\omega}_y - \omega_x \omega_z & \dot{\omega}_z + \omega_x \omega_y & \omega_y^2 - \omega_z^2 \\ \omega_x \omega_z & \dot{\omega}_y & -\omega_x \omega_z & \dot{\omega}_x + \omega_y \omega_z & \omega_z^2 - \omega_x^2 & \dot{\omega}_z - \omega_x \omega_y \\ -\omega_x \omega_y & \omega_x \omega_y & \dot{\omega}_z & \omega_x^2 - \omega_y^2 & \dot{\omega}_x - \omega_y \omega_z & \dot{\omega}_y + \omega_x \omega_z \end{bmatrix},$$

$$p = [b_{l_{xx}} \quad b_{l_{yy}} \quad b_{l_{zz}} \quad b_{l_{xy}} \quad b_{l_{xz}} \quad b_{l_{yz}}]^T - \quad - \quad -$$

$$b_l \quad K \quad t_1, t_2, \dots, t_K$$

$$A_{\omega} p = 0, \quad (11)$$

$$A_{\omega} = [\Phi_1^T \quad \Phi_2^T \quad \dots \quad \Phi_K^T]^T, \quad \Phi_k = \Phi(\dot{\omega}(t_k), \omega(t_k)), \quad k = 1, 2, \dots, K.$$

[16] (11)

$$\|A_{\omega} p\|^2 = (A_{\omega} p)^T A_{\omega} p = p^T A_{\omega}^T A_{\omega} p.$$

$$B p = 0, \quad B = A_{\omega}^T A_{\omega}. \quad (12)$$

$$(12) \quad p \neq 0$$

$B$

6.

$B$

5,

$p$

[17]

$c$ :

$$p_i = c \cdot (B)_{ji}, \quad i = 1, 2, \dots, 6, \quad (13)$$

$p_i - i -$

$p, (B)_{ji} -$

$(b)_{ji}$

$B,$

$j$

$(B)_{ji}$

$B$

$B$

6.

[16]

$b_l$

$$\hat{p} = [p_1 \quad p_2 \quad \dots \quad p_6]^T,$$

$$p_i \quad (13), \quad j, \quad -$$

$$v_j, \quad -$$

$$v_j = (B)_{ji}, \quad i = 1, 2, \dots, 6.$$

$$\cdot \quad -$$

:

$${}^b M \cdot \tau = -\kappa \cdot [-{}^b \hat{I}_n \cdot ({}^b \hat{\omega}_1) + ({}^b \hat{\omega}_1^\times) \cdot {}^b \hat{I}_n ({}^b \hat{\omega}_1) \cdot \tau / 2], \quad (14)$$

$${}^b M - \quad , \quad \tau - \quad , \quad \kappa -$$

$$p_{norm} \quad \tau \quad , \quad {}^b \hat{I}_n - \quad \hat{p}_{norm}, \quad -$$

$$\hat{p}_{norm}, \quad {}^b \hat{\omega}_1 - \quad -$$

$$t = t_{imp} \quad -$$

(14)

$${}^b \hat{I}_n ({}^b \hat{\omega}) + ({}^b \hat{\omega}^\times) {}^b \hat{I}_n ({}^b \hat{\omega}) = {}^b M, \quad (15)$$

$$(t_{imp}, t_{imp} + \tau)$$

$\omega \quad \dot{\omega}$

$$(15). \quad {}^b \hat{\omega}_1, \quad -$$

$${}^b \hat{I}_n = {}^b \hat{I}_n, \quad (10) \quad -$$

$$(t_k, t_{imp}) \quad {}^b \omega(t_k) = {}^b \hat{\omega}(t_k) \quad {}^b \dot{\omega}(t_k) = {}^b \hat{\dot{\omega}}(t_k)$$

$$k, \quad , \quad K.$$

$$, \quad \dots$$

$$( \quad f, \quad ).$$

$(3N \times 1)$

$$D_f f = B_f, \quad (16)$$

$$B_f = [{}^b M_x, {}^b M_y, {}^b M_z, 0, 0, 0]^T, \quad D_f = \begin{bmatrix} {}^b \hat{r}_{c0}^\times & | & {}^b \hat{r}_{c1}^\times & | & \dots & | & {}^b \hat{r}_{c,N-1}^\times \\ \hline E_{3 \times 3} & | & E_{3 \times 3} & | & \dots & | & E_{3 \times 3} \end{bmatrix},$$

$${}^b \hat{r}_{c0}^\times = -{}^b \hat{r}_c, \quad {}^b \hat{r}_{cn}^\times = {}^b \hat{r}_{c1}^\times + {}^b A_n^n r_{bn}, \quad n = 1, 3, \dots, N-1, \quad E_{3 \times 3} = \text{diag}(1, 1, 1).$$

(16)

$f$

$${}^b G_f \quad {}^n G_f$$

$${}^bG_f = [{}^bF_1 \mid {}^bF_2 \mid \dots \mid {}^bF_N], \quad {}^nG_f = [{}^1F_1 \mid {}^2F_2 \mid \dots \mid {}^NF_N],$$

$${}^nF_n = {}^nA_b {}^bF_n, \quad {}^bF_n = [f_{3n-2} \quad f_{3n-1} \quad f_{3n}]^T, \quad n=1,2,\dots,N,$$

$${}^bG_f = \dots, \quad {}^nG_f = \dots$$

$$\kappa, \quad {}^bI_n, \quad \hat{\mathbf{k}}, \quad {}^bI_n \cdot \hat{\mathbf{k}}$$

$${}^bI = \kappa \cdot {}^bI_n. \quad (17)$$

$$\omega_1 = {}^b\hat{\omega}_1, \quad t = t_{imp}, \quad \omega_2 = {}^b\hat{\omega}$$

$$t = t_{imp} + \tau, \quad \left. \begin{aligned} & {}^bI_{xx} (\omega_{2x} - \omega_{1x}) - ({}^bI_{yy} - {}^bI_{zz}) \omega_{xx} = {}^bM_x \cdot \tau \\ & {}^bI_{yy} (\omega_{2y} - \omega_{1y}) - ({}^bI_{zz} - {}^bI_{xx}) \omega_{yy} = {}^bM_y \cdot \tau \\ & {}^bI_{zz} (\omega_{2z} - \omega_{1z}) - ({}^bI_{zz} - {}^bI_{yy}) \omega_{zz} = {}^bM_z \cdot \tau \end{aligned} \right\}, \quad (18)$$

$$\left. \begin{aligned} \omega_{xx} &\approx (\omega_{2y} \omega_{2z} + \omega_{1y} \omega_{1z}) \cdot \tau / 2 \\ \omega_{yy} &\approx (\omega_{2z} \omega_{2x} + \omega_{1z} \omega_{1x}) \cdot \tau / 2 \\ \omega_{zz} &\approx (\omega_{2x} \omega_{2y} + \omega_{1x} \omega_{1y}) \cdot \tau / 2 \end{aligned} \right\}. \quad (19)$$

(18)

$${}^bI ({}^b\dot{\omega}) + ({}^b\omega^\times) {}^bI ({}^b\omega) = {}^bM \quad (20)$$

$$\tau \quad \omega_{xx}, \omega_{yy}, \omega_{zz}$$

(20) (

(19)

$$(17) - (19), \quad \hat{\mathbf{k}}$$

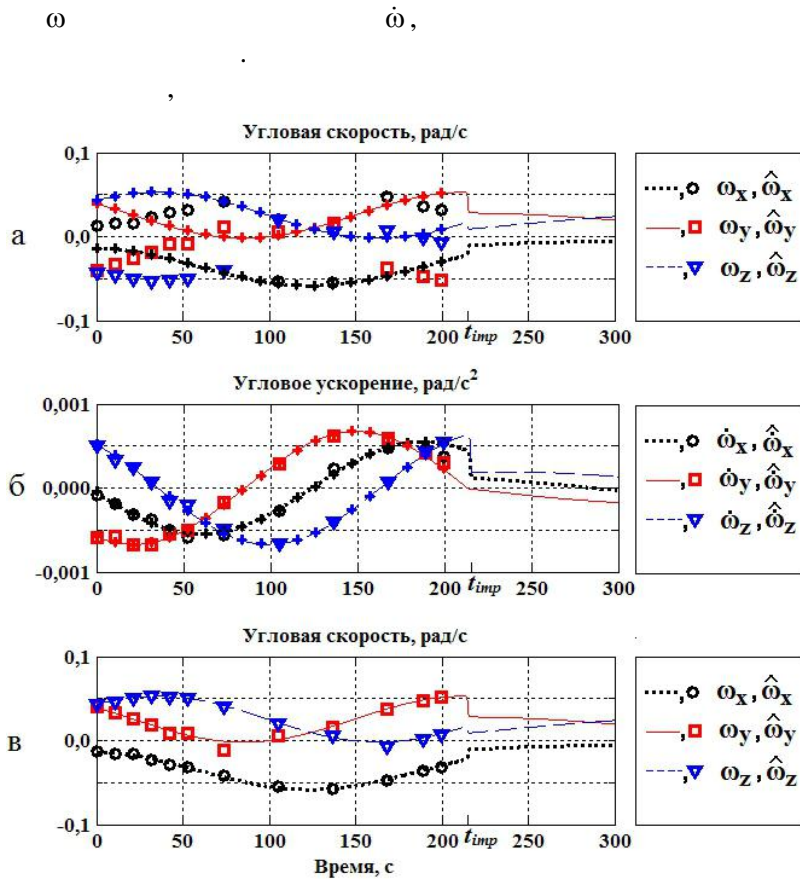
$$J \cdot \hat{\mathbf{k}} = {}^bM \cdot \tau,$$

$$J = \begin{bmatrix} bI_{nxx}(\omega_{2x} - \omega_{1x}) - (bI_{nyy} - bI_{nzz})\omega_{xx} \\ bI_{nyy}(\omega_{2y} - \omega_{1y}) - (bI_{nzz} - bI_{nxx})\omega_{yy} \\ bI_{nzz}(\omega_{2z} - \omega_{1z}) - (bI_{nzz} - bI_{nyy})\omega_{zz} \end{bmatrix}$$

J

$$J = b\hat{I}_n(b\hat{\omega}_2 - b\hat{\omega}_1) + [(b\hat{\omega}_2^\times)^b b\hat{I}_n(b\hat{\omega}_2) + (b\hat{\omega}_1^\times)^b b\hat{I}_n(b\hat{\omega}_1)] / 2 \cdot \tau$$

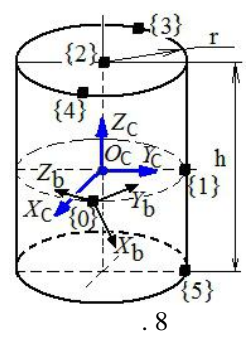
$O_b X_b Y_b Z_b$



. 7

$$\hat{\omega} \quad (7), \quad \hat{\dot{\omega}}$$

(8)

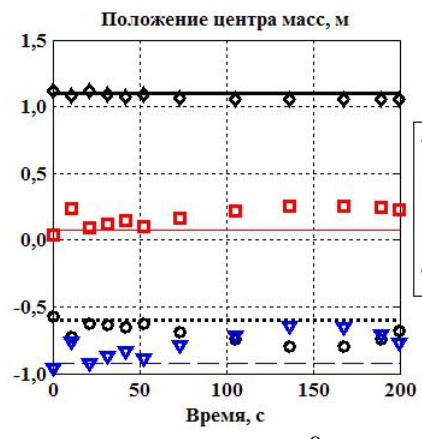


$h = 2,6$ ,  $r = 1,1$ ,  $\rho = 1000$   
 $\text{diag}(1168 \ 1168 \ 605)$   
 $O_c X_c Y_c Z_c$

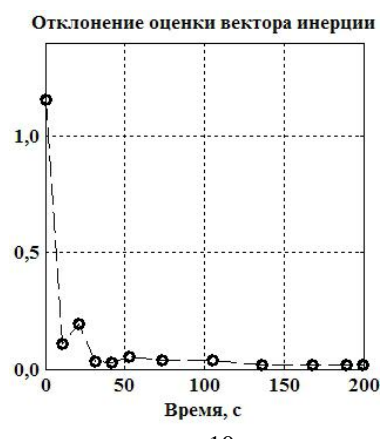
$$[0,0241 \ 0,0204 \ 0,0510]^T / O_b X_b Y_b Z_b$$

$$[-0,0137 \ 0,0394 \ 0,0431]^T / O_c X_c Y_c Z_c$$

10 %



. 9



. 10

$$r_{cx}, r_{cy}, r_{cz} \quad |r_c| \quad b_{r_c}$$

10

$\rho$

$$\hat{p} \quad p, \quad -$$

$$: \hat{p}_{norm} = \hat{p} / \|\hat{p}\| \quad p_{norm} = p / \|p\|.$$

$$\Delta\hat{p} = \hat{p}_{norm} - p_{norm},$$

$$t_{imp} \quad 215, \quad \tau \quad 1. \quad -$$

(16).

$$\hat{\kappa} \quad \kappa, \quad -$$

$$(11),$$

$$\hat{\kappa} / \kappa$$

$$0,86 \div 1,09 \quad (\kappa = 1731).$$

$$\kappa \quad 800. \quad -$$

$${}^b G_f = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3,11 & -3,38 & 0,27 \\ 0 & 0 & 0 & -7,30 & 0,0 & 7,30 \end{bmatrix},$$

$$\hat{p} = [917,0 \quad 208,1 \quad 202,9 \quad 1056,5 \quad -155,6 \quad 1048,8] \cdot 2$$

$$p = [886,7 \quad 199,2 \quad 199,2 \quad 1027,5 \quad -140,8 \quad 1027,5] \cdot 2.$$

