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Posture control of a 3-RPS pneumatic parallel platform with parameter initialization and an adaptive robust method

Key words: Parameter initialization; Adaptive robust control; Parallel mechanism; Pneumatic cylinders

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Motivation

- Due to the compressibility of air and nonlinear characteristics of pneumatic elements, pneumatic servo control is very difficult.
- For the parallel platform used in virtual reality entertainment equipment (a four-dimensional (4D) movie chair), posture condition and load forces vary heavily during ordinary operation.

Main idea

1. A direct part is integrated into the robust controller design to raise the transient performance.

2. A new method integrated with parameter initialization (ARCPI) is proposed for posture control for the parallel pneumatic manipulator to overcome the disadvantages caused by the variation of the initial estimation value.

1. Modeling of a 3-RPS pneumatic platform-Kinematics

$$
{}^{A}_{B}T = \begin{bmatrix} c\beta c\gamma & -c\beta s\gamma & s\beta & X_{bo} \\ c\alpha s\gamma + s\alpha s\beta c\gamma & c\alpha c\gamma - s\alpha s\beta s\gamma & -s\alpha c\beta & Y_{bo} \\ s\alpha s\gamma - c\alpha s\beta c\gamma & c\gamma s\alpha + c\alpha s\beta s\gamma & c\alpha c\beta & Z_{bo} \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Transition matrix

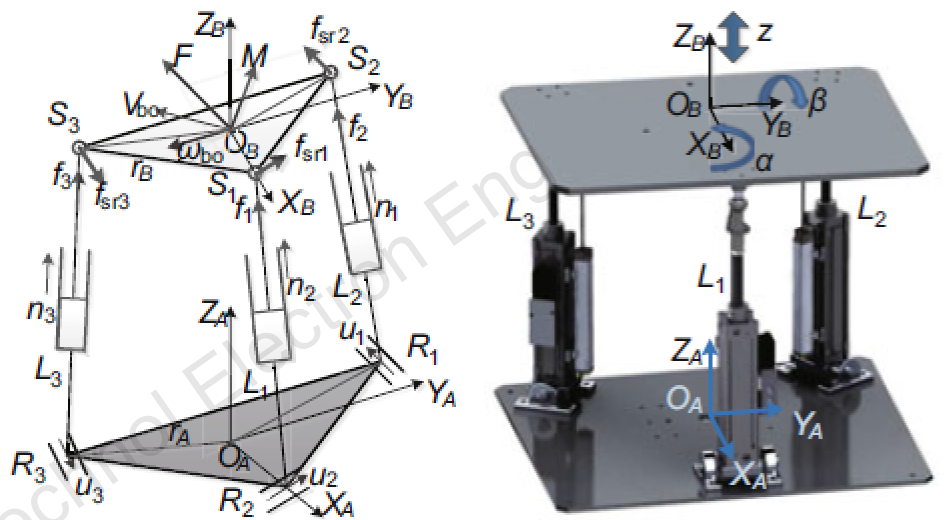
$$
\begin{cases} {}^{A}Y_{bo} = r_b(\cos\beta\sin\gamma) \\ {}^{A}X_{bo} = \dfrac{r_b}{2}(\cos\beta\cos\gamma + \sin\alpha\sin\beta\sin\gamma - \cos\alpha\cos\gamma) \\ \gamma = -\arctan\dfrac{\sin\alpha\sin\beta}{\cos\alpha + \cos\beta} \end{cases}
$$

constraint equations

$$
\vec{L}_i = {}^{A}_{B}T\,{}^{B}P'_{si} - {}^{A}P_{Ri} = {}^{A}_{B}R_{xyz}\,{}^{B}P_{si} + {}^{A}P_{bo} - {}^{A}P_{Ri}
$$

$$
\vec{L}_1 = \begin{bmatrix} r_b c\beta c\gamma + {}^{A}X_{bo} - r_a \\ r_b(c\alpha s\gamma + s\alpha s\beta c\gamma) + {}^{A}Y_{bo} \\ r_b(s\alpha s\gamma - c\alpha s\beta c\gamma) + {}^{A}Z_{bo} \end{bmatrix}
$$

Inverse kinematics



Mechanical structure of the 3-RPS pneumatic platform

$X_d(\alpha(t), \beta(t), Z(t))$ Workspace

$x_d(L1(t), L2(t), L3(t))$ Jointspace

2. Modeling of a 3-RPS pneumatic platform-Dynamics

Pressure diff   friction   Load

$$\boldsymbol{M}_{\mathrm{e}}\ddot{\boldsymbol{x}} = \boldsymbol{A}_{\mathrm{a}}\boldsymbol{p}_{\mathrm{L}} - \boldsymbol{b}\dot{\boldsymbol{x}} - \boldsymbol{A}_{\mathrm{f}}\boldsymbol{S}_{\mathrm{f}}(\dot{\boldsymbol{x}}) - \boldsymbol{F}_{\mathrm{L}} + \boldsymbol{f}_{\mathrm{n}} + \widetilde{\boldsymbol{f}}_{0},$$

$$\dot{\boldsymbol{p}}_{\mathrm{L}} = \boldsymbol{q}_{\mathrm{L}} + \boldsymbol{F}_{\mathrm{p}} + \boldsymbol{d}_{\mathrm{n}} + \widetilde{\boldsymbol{d}}_{0},$$

disturbance   Modeling error

$$\boldsymbol{M}_{\mathrm{e}} = \mathrm{diag}(m_1, m_2, m_3)$$

$$\boldsymbol{p}_{\mathrm{L}} = [p_{\mathrm{L}1}, p_{\mathrm{L}2}, p_{\mathrm{L}3}]^{\mathrm{T}} \quad \boldsymbol{q}_{\mathrm{L}} = [q_{\mathrm{L}1}, q_{\mathrm{L}2}, q_{\mathrm{L}3}]^{\mathrm{T}}$$

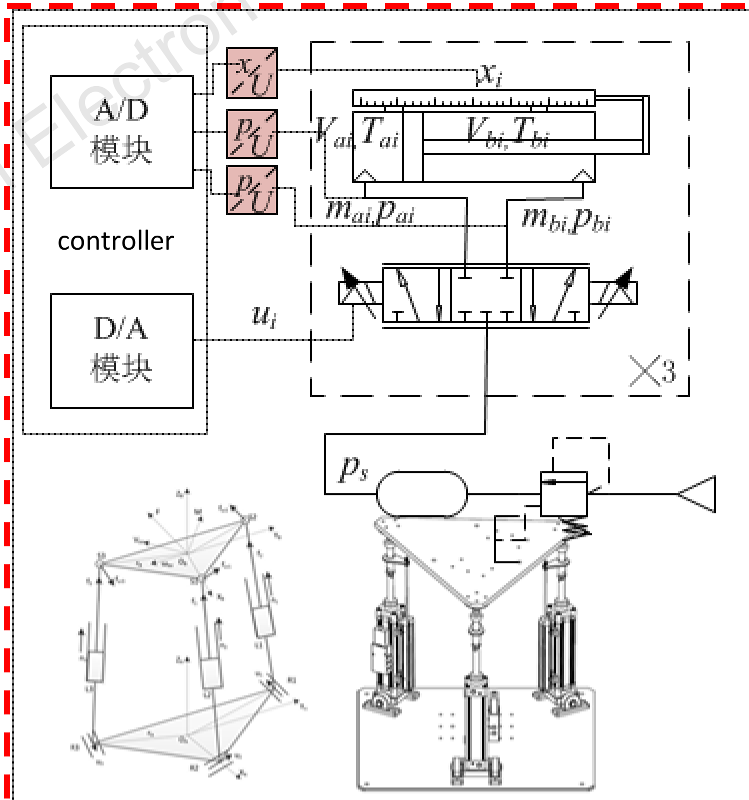
$$\boldsymbol{F}_{\mathrm{p}} = [F_{\mathrm{p}1}, F_{\mathrm{p}2}, F_{\mathrm{p}3}]^{\mathrm{T}} \quad p_{\mathrm{L}i} = p_{ia} - k_{i\mathrm{area}} p_{ib}$$

$$q_{\mathrm{L}i} = \frac{\gamma_{\mathrm{a}} R}{H_{\mathrm{p}} V_{ia}}\left(\dot{m}_{ia\mathrm{in}} T_{\mathrm{s}} - \dot{m}_{ia\mathrm{out}} T_{ia}\right) - \frac{\gamma_{\mathrm{a}} R}{H_{\mathrm{p}} V_{ib}}\left(\dot{m}_{ib\mathrm{in}} T_{\mathrm{s}} - \dot{m}_{ib\mathrm{out}} T_{ib}\right),$$

Mass part

$$F_{\mathrm{p}i} = -\frac{\gamma_{\mathrm{a}} A_{ia}}{V_{ia}}\dot{x}_i p_{ia} - \frac{\gamma_{\mathrm{a}} A_{ib}}{V_{ib}}\dot{x}_i p_{ib} + \frac{\gamma_{\mathrm{a}} - 1}{H_{\mathrm{p}} V_{ia}}\dot{Q}_{ia} - \frac{\gamma_{\mathrm{a}} - 1}{H_{\mathrm{p}} V_{ib}}\dot{Q}_{ib}.$$

Energy part



3. Load parameters initialization/estimation

Determination of the parameters' initial values can help the system status converge into a specific stable condition faster, compared with nonchangeable initial factors. To estimate these numbers, identification of the dynamic parameters of the 3-RPS system can be helpful.

Atkeson, Christopher G, An, Chae H, Hollerbach, John M, 1985. Rigid body load identification for manipulators. Decision and Control, 1985 24th IEEE Conference on, p.996–1002.

Load compensation

Gibbs-Appell equation

$$W(q,\dot{q},\ddot{q})\cdot\Phi=\tau_L$$

Load paras vector

$$\Phi=\begin{bmatrix}[M_\Phi] & [I_\Phi] & [\Phi_{fri}]\end{bmatrix}^T$$

Observation matrix

$$W_r^I\cdot\Phi_b^I+(F_{f_i}-Z^T F_{f_e})=\tau_L$$

reducing

$$[{F_{Bd}}^T,\tau_B^T]^T=W_c^T\Phi_c$$

Load paras estimation

$$\hat{\Phi}_c=\frac{W_c U_c^T}{W_c^T W_c}$$

Definitions and calculation

$$W_c^T=\begin{bmatrix}P_W & C_{W1} & 0 & N\cdot B\\ 0 & C_{W2} & C_{WP} & 0\end{bmatrix}$$

$$C_{W1}=C(\dot{\omega}_{O_B})+C(\omega_{O_B})C(\omega_{O_B}),\ C_{W2}=C(\ddot{P}_{O_B}-g),\ C_{WP}=D(\dot{\omega}_{O_B})+C(\omega_{O_B})D(\omega_{O_B}).$$

$$N=\begin{bmatrix}n_1 & n_2 & n_3\end{bmatrix}$$

$$B=\begin{bmatrix}\mathrm{diag}(\dot{x}_1,\dot{x}_2,\dot{x}_3) & \mathrm{diag}(S_{c1},S_{c2},S_{c3})\end{bmatrix}_{3\times 6}$$

$$F_{Be}=F_{Bd}-F_{fs}=$$

$$m\ddot{P}_{O_B}-mg+\dot{\omega}_{O_B}\times mc+\omega_{O_B}\times(\omega_{O_B}\times$$

$$\tau_B=I_{O_B}\dot{\omega}_{O_B}+\dot{\omega}_{O_B}\times(I_{O_B}\omega_{O_B})$$

$$+mc\times(\dot{\omega}_{O_B}\times c)+mc\times(\omega_{O_B}\times(\omega_{O_B}\times c)$$

$$+mc\times\ddot{P}_{O_B}-mc\times g$$

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

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

$$I_{O_B}=I_{O_B}^T=\begin{bmatrix}I_{11} & I_{12} & I_{13}\\ I_{21} & I_{22} & I_{23}\\ I_{31} & I_{32} & I_{33}\end{bmatrix}$$

4. Controller design – fast compensators

To compensate for the uncertainty and the influence caused by estimations, a fast dynamic compensator is integrated in the controller design.

Meng, Deyuan, Tao, Guoliang, Zhu, Xiaocong, 2013. Integrated direct/indirect adaptive robust motion trajectory tracking control of pneumatic cylinders. *International Journal of Control*, **86**(9):1620–1633

1st level calculation

ped

$$e_s = \dot{e} + K_x e \qquad e_p = p_L - p_{Ld}$$

$$\dot{e}_s = \ddot{e} + K_x(\dot{x} - \dot{x}_d)$$

$$p_{Ld} = p_{Lda1} + \boxed{p_{Lda2}} + p_{Lds1} + p_{Lds2}$$

$$p_{Lda1} = \frac{1}{\bar{A}_a}\left[-\varphi_a^T\hat{\theta}_a + M_e\ddot{x}_d - M_e K_x e\right]$$

$$p_{Lds1} = -\frac{1}{\bar{A}_a}K_p e_s$$

$$p_{Lds2} = -\frac{1}{\bar{A}_a}\frac{H_1^2(t)}{4\eta_1}e_s$$

$$d_{c1} + R_1(t) = -\varphi_a^T\tilde{\theta}_a + \tilde{f}_0$$

$$p_{Lda2} = -\frac{1}{\bar{A}_a}\hat{d}_{c1}$$

2nd level calculation

qed

$$\dot{e}_p = q_L + F_p + \varphi_b^T\theta_b + \tilde{d}_0 - \dot{p}_{Ld}$$

$$q_{Ld} = q_{Lda1} + \boxed{q_{Lda2}} + q_{Lds1} + q_{Lds2}$$

$$q_{Lda1} = -\bar{A}_a e_s - F_p - \varphi_b^T\hat{\theta}_b + \dot{p}_{Ld}$$

$$q_{Lds1} = -K_q e_p$$

$$q_{Lds2} = -\frac{H_2^2(t)}{4\eta_2}e_p$$

$$d_{c2} + R_2(t) = -\varphi_b^T\tilde{\theta}_b + \tilde{d}_0$$

$$q_{Lda2} = -\hat{d}_{c2}$$

Low freq

High freq

5. Results

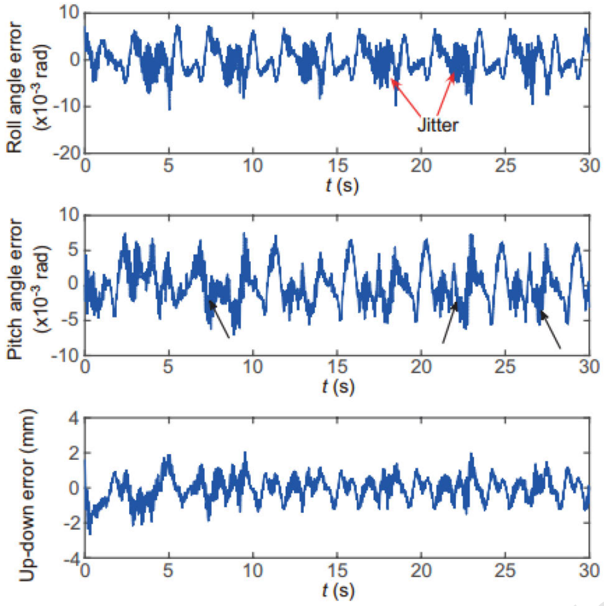


Fig. 7 Vibration caused by initial value difference and load change (m=75 kg): roll angle, pitch angle, and up-down tracking errors of 3-RPS

Tracking error w/o ARCPI method

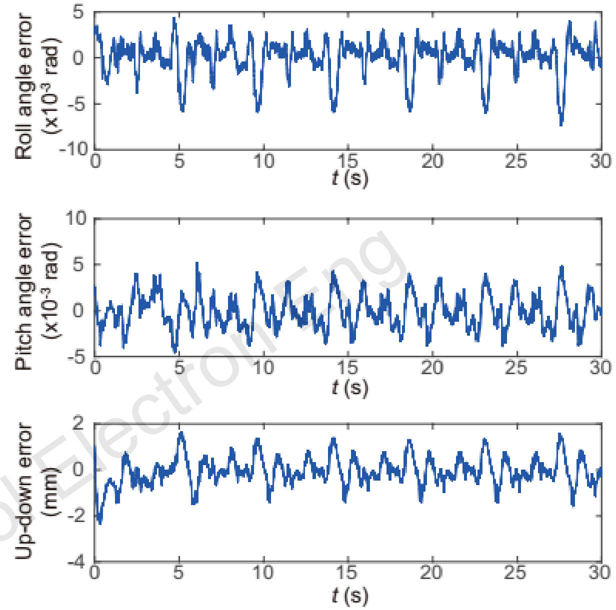


Fig. 8 Tracking with initialization (m=75 kg): (a) roll angle, pitch angle, and up-down tracking errors of 3-RPS;

Tracking error w ARCPI method

Table 3 Tracking error analysis e_F (m=50 kg)

Parameter	SMC	ARC	ARCPI
Roll (rad)	0.011	0.0046	0.0032
$Roll_{rel}$	3.9%	1.6%	1.1%
Pitch (rad)	0.013	0.0057	0.0037
$Pitch_{rel}$	4.1%	1.8%	1.2%
Heave (mm)	3.6	2.0	1.4
$Heave_{rel}$	4.0%	2.2%	1.6%

Table 4 Tracking error analysis e_{rms} (m=50 kg)

Parameter	SMC	ARC	ARCPI
Roll (rad)	0.0070	0.0023	0.0016
$Roll_{rel}$	2.70%	0.82%	0.57%
Pitch (rad)	0.074	0.0028	0.0020
$Pitch_{rel}$	2.30%	0.88%	0.63%
Heave (mm)	2.1	0.85	0.54
$Heave_{rel}$	2.30%	0.94%	0.60%

Tracking error analysis

5. Conclusions

- Parameter uncertainty and nonlinear features can be estimated and inhibited by online estimation methods and robust parts of the controller.
- The experimental results indicated that the unknown parameters are indeed bounded and converge.
- The parameter identification not only prevents the vibration phenomenon but also decreases the estimation time when given a set of better initial parameter values.
- Compared to previous methods such as SMC and the basic ARC controller, the proposed method can improve the tracking performance by the integrated direct/indirect adaptive robust design.