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Robust Adaptive Control of a Bimanual 3T1R Parallel Robot with Gray-Box Model toward Prescribed Performance

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Abstract

In this work, a gray-box-model-based control structure is proposed, with the retained inertial dynamics are directly derived by the principle of virtual work and the other parts are estimated by adaptive neural networks. This ensures calculation efficiency and integrity of the dynamics. Moreover, a prescribed performance function is constructed to ensure the specified tracking requirements both in transient and steady states. On the basis, the robust integral of signum of error term is incorporated to compensate the structural and unstructural uncertainties, which further improves the robustness during high-frequency motion. Comparative real-time experiments have been performed on the actual robot with attainment of the predefined performance.

Modeling of the Robot

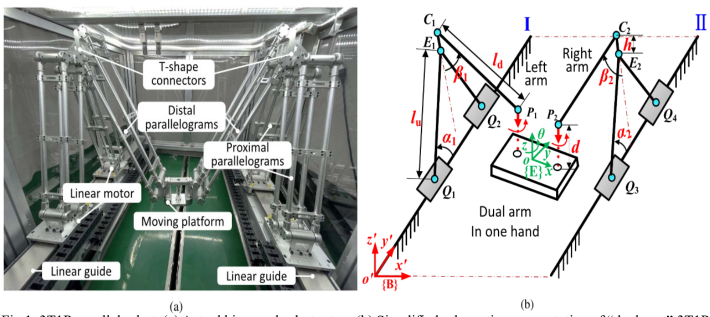

Fig.1. 3T1R parallel robot. (a) Actual bimanual robot setup. (b) Simplified schematic representation of "dual-arm" 3T1R robot.

- **Modeling of Inertia Dynamics**

During high-speed repetitive pick-and-place applications, a large portion of the driving force of the robot is used to overcome the inertia force. Thus, it is worth to accurately model the **inertial dynamics** for precision motion.

$$M(q)=m_q G^{\mathrm{T}} G+\sum_{k}^{2} J_k^{\mathrm{T}} \operatorname{diag}\{m_k I, 0\} J_k+\operatorname{diag}\{m_p I, I_p\}+\sum_{i}^{4} G^{\mathrm{T}} J_{l_i}^{\mathrm{T}} \operatorname{diag}\{m_{l_i} I, I_{l_i}\} J_{l_i} G+\sum_{j}^{2} J_{d_j}^{\mathrm{T}} \operatorname{diag}\{m_d I, I_{d_j}\} J_{d_j}$$

Controller Design

- **Control Objective**

The control objective is to design a continuous controller, which ensures x_1 tracks the time-varying trajectory x_d with prescribed bounded tracking error $\tilde{x}_1$, whereas the vibration of the moving platform of the robot is suppressed.

$$\begin{cases}\dot{\tilde{x}}_1=\tilde{x}_2\\ \dot{\tilde{x}}_2=M^{-1}(\tau_d-\tau)+f(x_1,x_2)+\ddot{x}_d,\end{cases} \text{and } f(x_1,x_2)=M^{-1}(Cx_2+G+f_c(x_2)).$$

- **PPF for Tracking**

The tracking errors of the active prismatic joints $\tilde{x}_1$ are required to satisfy the PPF, which specify tracking precision as

$$-\underline{\delta}_i \rho_i(t)<e_i(t)<\bar{\delta}_i \rho_i(t)$$

- **Transformed Error Dynamics With PPF**

An error transformation is introduced as

$$e_i(t)=\rho_i(t)\phi_i(\xi_i)$$

The acceleration of the transformed error vector is derived as

$$\ddot{s}_1=\Psi M^{-1}(\tau_d-\tau)+\Psi(f(x_1,x_2)+\ddot{x}_d)+F_e(\tilde{x}_1,\tilde{x}_2)$$

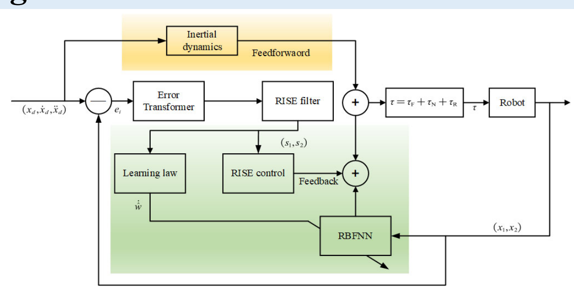

Fig.2. Overview of the control block diagram.

- **RISE Controller With PPF**

The dominant inertial dynamics has been derived in Section II for model-based compensation, and forms the semimodel-based control strategy as

$$\tau=\tau_{\mathrm{F}}+\tau_{\mathrm{N}}+\tau_{\mathrm{R}}, \tau_{\mathrm{F}}=M\ddot{x}_d, \tau_N=M\left(\int_0^t \hat{W}^{\mathrm{T}} h(x_1,x_2)dt\right),$$

$$\tau_{\mathrm{R}}=M\left(\bar{k}_p s_2-\bar{k}_p s_2(0)+\int_0^t\left[\bar{k}_p \mu_2 s_2-\omega \operatorname{sgn}(s_2)\right]dt.\right.$$

Experiments

- **Pick-and-Place Profile Tracking Test**

By comparison, the amplitude of SNRC in steady state is smaller, the robustness is stronger, and the tracking performance is stronger. This verifies that the proposed SNRC can achieve high speed pickup and place function.

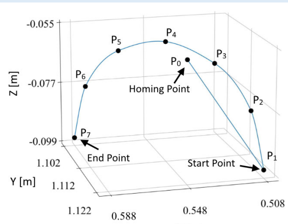

Fig.5. 3-D view of the pick-and-place path for bimanual 3T1R in the task space.

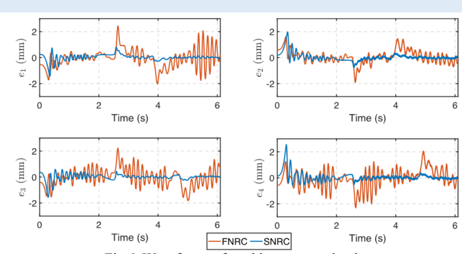

Fig.6. Waveforms of tracking error under the pick-and-place profile.