$$K_1(\lambda) = \frac{N_{K1}(\lambda)}{1+0.7548\lambda}$$

$$N_{K1}(\lambda) = 12.82z^4 - 15.57z^3 - 4.591z^2 + 301.0z - 27.68 - 64.54\lambda - 4.726\lambda^2 + 18.18\lambda^3 + 1.468\lambda^4 - 6.142\lambda^5 - 1.791\lambda^6 + 12.03\lambda^7 - 6.343\lambda^8$$

The simulation results (Fig. 4) show that, for the nominal plant, the tracking error is very low when the reference is input, and the applied voltage during the transient response is moderately restricted. For the heaviest inertial load, the system still remains stable and its output tracks the reference input without steady-state error.

The experimental system is shown in Fig. 5. Figure 6 shows the results for the heaviest load. Just as for the simulation results, the control system is stable even when the load is changed; and during the transient response, the tracking error is very low. On the other hand, since the experimental system was originally designed for student practice, the precision is not very high (optical encoder: 16 cycles per turn; gear box: 64:8:1). The voltage applied to the motor reached saturation (± 5 V), and the influence of the dead zone was marked. For these reasons, the response was not as good as the simulations; but the features of the design method, namely, the robust stability resulting from the sampled-data $\mathcal{H}_\infty$ control and the quick response due to the preview, were demonstrated by the experimental results.

6 Conclusions

This paper describes a design method for digital tracking control systems for a continuous plant with structured uncertainties. A TDF tracking control system configuration is employed. Regarding the feedback controller, in order to robustly stabilize a plant with structured uncertainties, the design problem is first formulated as a sampled-data $\mathcal{H}_\infty$ control problem, and then transformed into an equivalent discrete-time $\mathcal{H}_\infty$ control problem. A reduced-order output feedback controller with an order less than that of the plant has been designed. The feedforward controller is parametrized based on the feedback controller, with the free parameter being chosen to achieve the desired transient response using a preview strategy. The design method was applied to the control of an arm robot, and the results of both simulations and experiments demonstrate that the integration of a TDF control system configuration, sampled-data $\mathcal{H}_\infty$ control, and preview control is a powerful tool for the control of mechatronic systems.

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A Comment on Stability of Telerobotic Manipulations

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Appendix A in [1] describes a condition for stability of a telerobotic system using the multivariable Nyquist criteria derived in [2]. In order to guarantee the stability of the closed loop system, Eq. ($A1$) in Appendix A of Ref. [1] must be guaranteed as written below:

$$\det(I+RQ+\varepsilon RGH) \neq 0 \quad \forall \omega \in [0,\infty] \quad \textit{and} \quad \forall \varepsilon \in [0,1] \tag{1}$$

The condition $\forall \varepsilon \in [0,1]$ is missing in Appendix A of Ref. [1] and is added here. This condition states that as $\det(I+RQ)$ is continuously deformed to become $\det(I+RQ+\varepsilon RGH)$, the magnitude of $\det(I+RQ+\varepsilon RGH)$ should not pass through the origin of the s-plane for all frequencies. This condition alternatively indicates that the complete area of the frequency plot does not include the origin of the s-plane. Obviously condition $\forall \varepsilon \in [0,1]$ should be incorporated into all equations derived after Eq. ($A1$) including Eqs. (27) and (28). The author thanks Dr. Wen-Hong Zhu of the Canadian Space Agency who noticed this missing condition.

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