Human Control Strategies in Manual Pursuit Tracking of Sinusoidal Signals

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Introduction

Humans have extraordinary ability to effectively compensate unforeseen errors during manual tracking tasks. When the reference signal of the tracking tasks is predictable, humans may use feedforward control strategies to improve the tracking performance. We propose a novel system identification methods to estimate both feedback and feedforwrd controllers in human operators during manual tracking tasks. The proposed method has applications in many fields including automotive engineering and rehabilitation.

Experiments

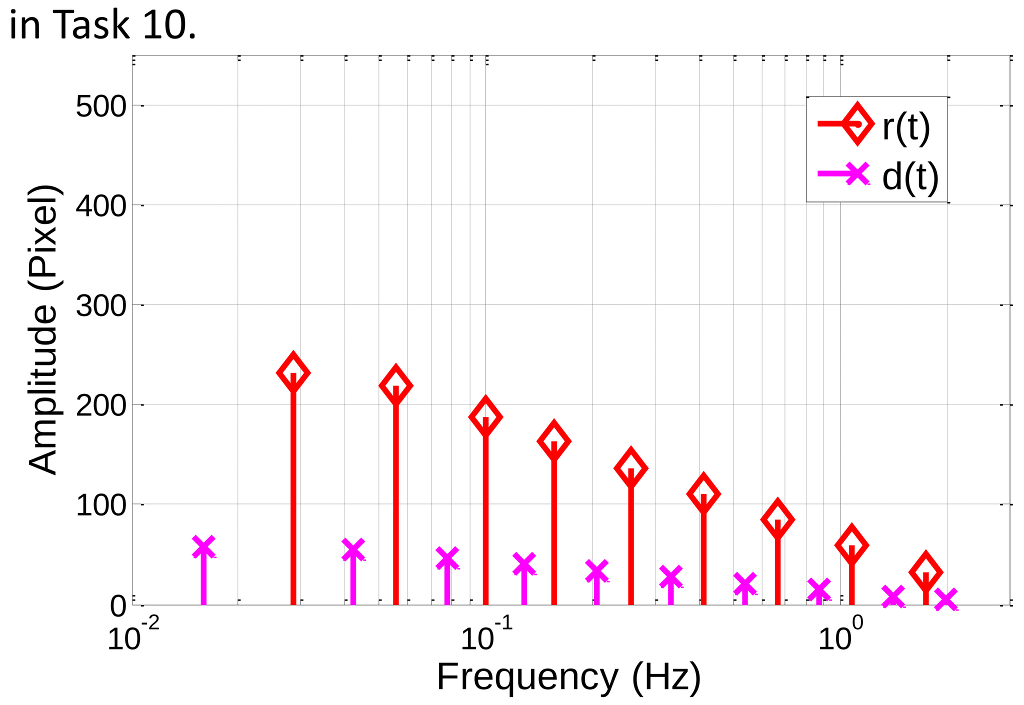
- The tracking task was presented on a LCD display in a "pursuit" configuration as shown on the right. The animation update rate was 50 Hz. The display measured 55×36 cm with 1920×1200 pixel resolution was placed at a distance of about 120 cm from the subjects' eyes.
- Subjects used a motorized haptic wheel to generate their control inputs, i.e., $u(t)$. Subjects generally used a range of ± 90 degrees from the wheel's initial position. The angular position of the wheel, $u(t)$, was measured by an optical encoder. The rotational stiffness of the wheel was set to 0.14 Nm/rad over the full rotational range.
- The plant is an integrator.

$$P(s) = \frac{40}{s}.$$

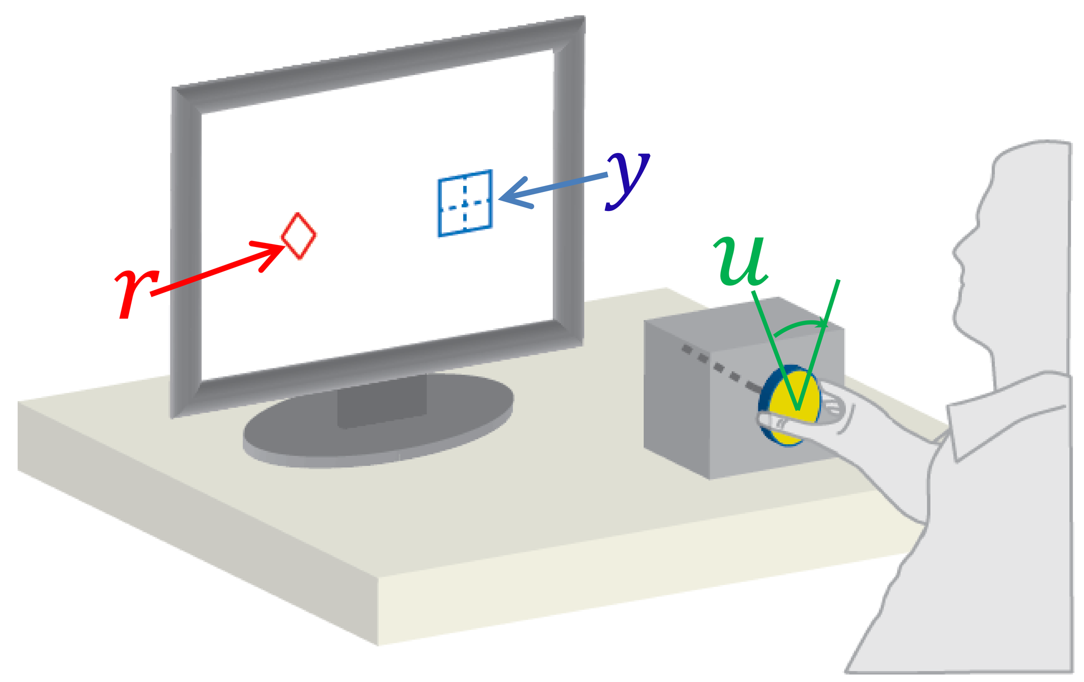
- Six subjects, all male, aged 20-31 years, participated in this study. They were instructed to minimize the tracking error $e(t) \triangleq r(t) - y(t)$ presented on the display.
- Each subject completed ten tracking tasks. The order of the ten tracking tasks was randomized for each subject.

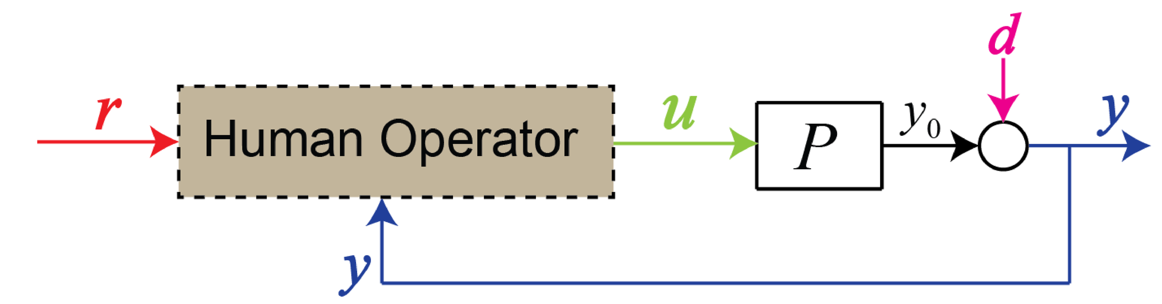
Task	$r(t)$ (pixel)	$d(t)$ (pixel)
Task 1	$540\sin(\omega_1^r t + \varphi_1)$	$\sum_{i=1}^{9} B_i \sin(\omega_i^d t + \varphi_i)$
Task 2	$540\sin(\omega_2^r t + \varphi_2)$	
Task 3	$540\sin(\omega_3^r t + \varphi_3)$	
Task 4	$540\sin(\omega_4^r t + \varphi_4)$	
Task 5	$540\sin(\omega_5^r t + \varphi_5)$	
Task 6	$540\sin(\omega_6^r t + \varphi_6)$	
Task 7	$540\sin(\omega_7^r t + \varphi_7)$	
Task 8	$540\sin(\omega_8^r t + \varphi_8)$	
Task 9	$540\sin(\omega_9^r t + \varphi_9)$	
Task 10	$\sum_{i=1}^{9} A_i \sin(\omega_i^r t + \varphi_i)$	

- The frequencies of $d(t)$ are different from those of $r(t)$. Also the magnitude of $d(t)$ is much smaller than that of $r(t)$. The following figure shows the amplitudes and frequencies of $r(t)$ and $d(t)$ in Task 10.



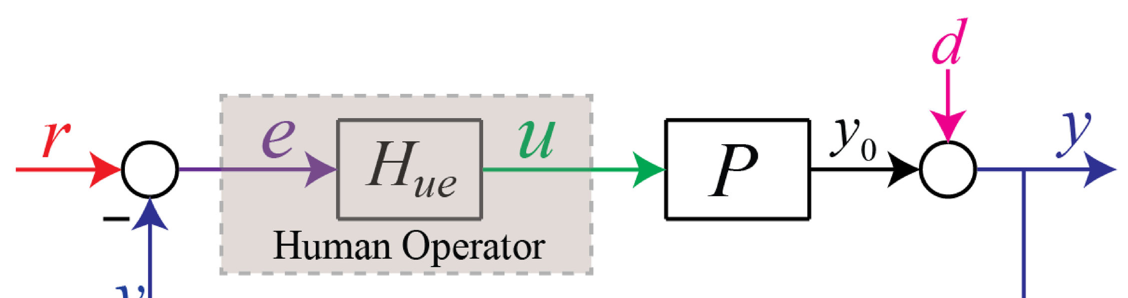
- The experiment for each tracking task lasted 240s, of which the last 220s were used as the measurement data.





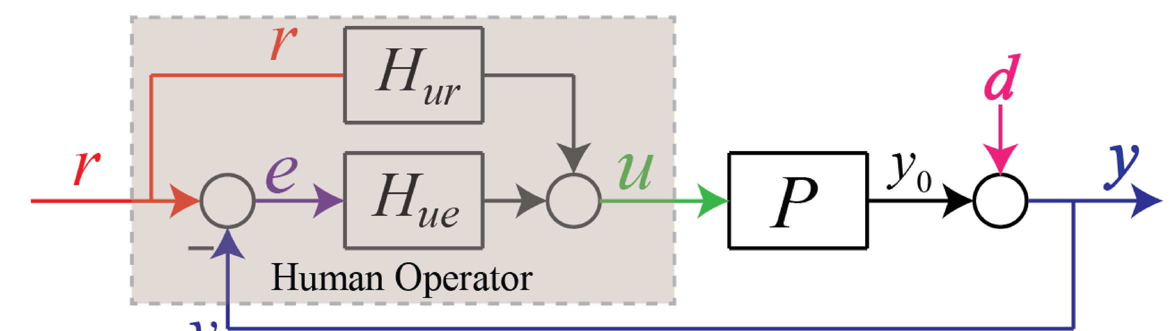
- r: reference signal (red diamond in pixel)
- y: output signal (blue square in pixel)
- u: control signal (handwheel position in degree)
- d: disturbance signal (in pixel)

Human Operator Models



Compensatory Control Model

- The **compensatory model** describes the behavior of human operators when only the error signal is available to the human operator and the reference/disturbance signals are unpredictable.
- From a viewpoint of control systems, the sensitivity function $S(s) \triangleq \frac{1}{1+L(s)}$ is the transfer function for disturbance rejection and the complementary sensitivity function $T(s) \triangleq \frac{L(s)}{1+L(s)}$ is the transfer function of reference tracking because
$$Y(s) = T(s)R(s) + S(s)D(s).$$
Furthermore, the compensatory control model has a fundamental limit between reference tracking and disturbance rejection performance due to the "**complementarity constraint**"
$$T(s) + S(s) = 1.$$
- A useful and widely employed model to describe a human operator's compensatory control is **McRuer's crossover model**. The crossover model assumes that near gain crossover frequency the human operator and plant together approximate an integrator k_c/s with a time delay τ :
$$L(s) = H_{ue}(s)P(s) \approx \frac{k_c e^{-s\tau}}{s}.$$



Feedforward Control Model

- If the reference signal is predictable and both reference and output signals are available to human perception, operators may use combined feedforward and compensatory control strategies as described in the **feedforward control model**.
- Compared with the compensatory control model, the feedforward controller $H_{ur}(s)$ can improve the tracking performance while the disturbance rejection performance depends only on feedback controller $H_{ue}(s)$.
$$Y(s) = T_{\text{pursuit}}(s)R(s) + S(s)D(s),$$
$$\mathrm{E}(s) = \left[1 - T_{\text{pursuit}}(s)\right]R(s) - S(s)D(s),$$
where $T_{\text{pursuit}}(s) = T(s) + H_{ur}(s)P(s)S(s)$.
From a viewpoint of control system, a good feedforward controller is to approximate the plant, that is
$$H_{ur}(s)P(s) \approx 1.$$
- There is very limited research work on identifying feedforward controllers in existing literatures.

Objective: propose a novel method to identify both feedforward and feedback controllers in feedforward control model when human tracking single sine singles or peudorandom sum-of-sine signals.

Identification Methods

The idea is to make use of the complementarity constraint.

$\hat{T}(s) = -\frac{\widehat{Y_0}(s)}{\widehat{D}(s)}$ at frequencies of $d(t)$
where $\widehat{Y_0}(s)$ is the FFT of $y_0(t)$
and $\widehat{D}(s)$ is the FFT of $d(t)$

From $\hat{T}(s)$, we can further derive $H_{ue}(s)$

$$\hat{S}(s) = 1 - \hat{T}(s)$$

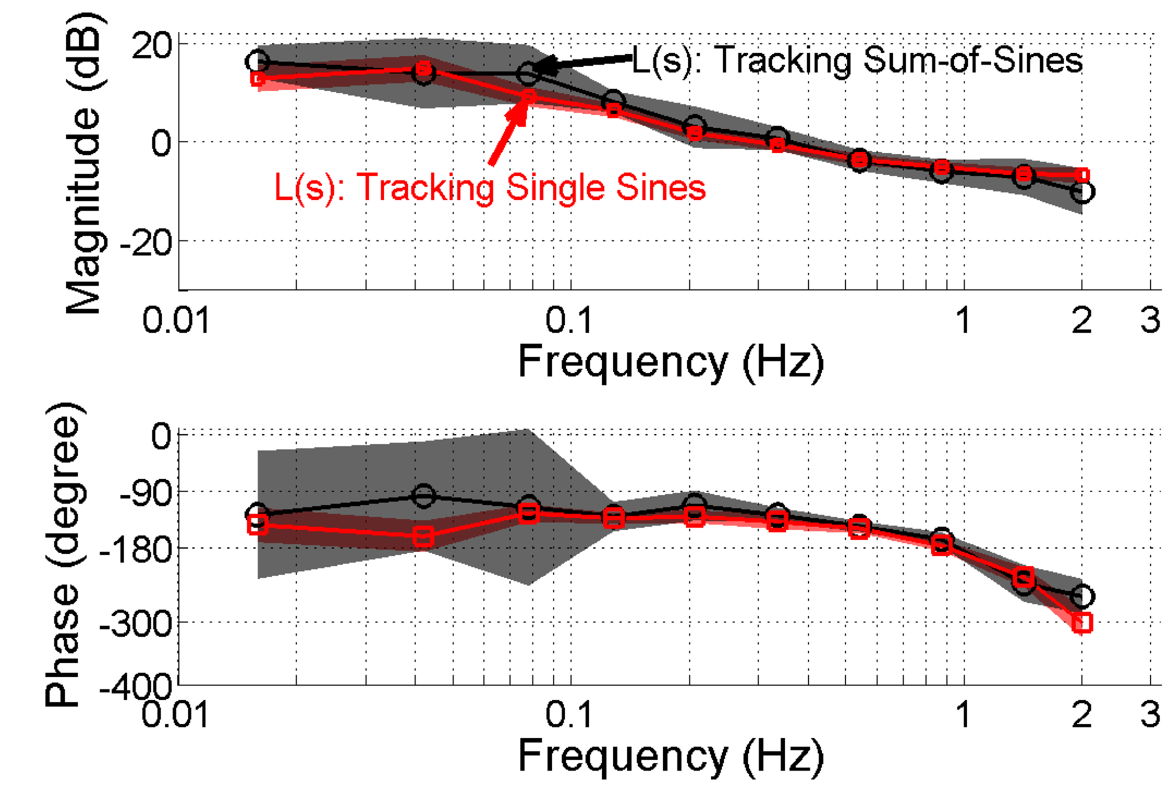
Using complementarity constraint, we can derive $\hat{S}(s)$.

$$\widehat{H}_{ur}(s)\hat{P}(s) = \frac{\frac{\widehat{Y_0}(s)}{\hat{R}(s)} - \hat{T}(s)}{\hat{S}(s)}$$

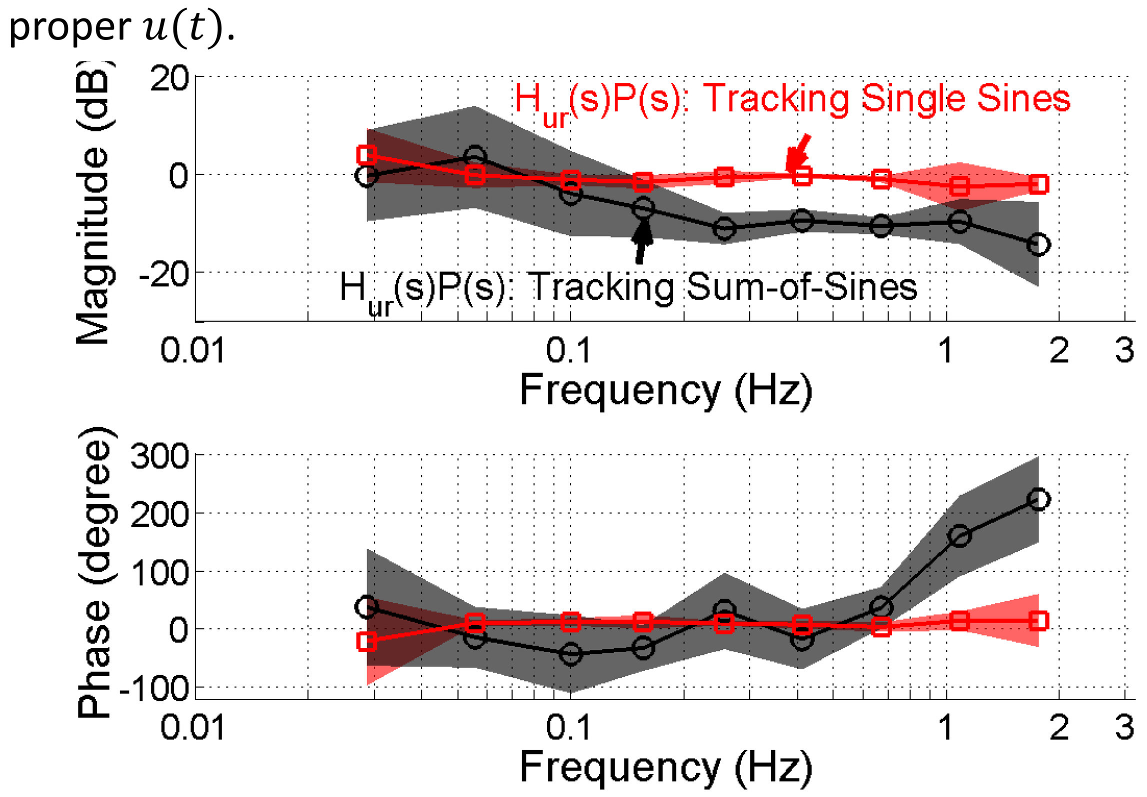
We can further derive $\widehat{H}_{ur}(s)\hat{P}(s)$ from system transfer functions.

Results

- The average estimates of frequency responses of $L(s)$ for all subjects are shown in the following figure. We averaged the frequency response estimates of $L(s)$ in Tasks 1-9 for all subjects. The solid lines with markers stand for the mean values of estimated magnitude and phase responses and the shaded regions indicate the 95% confidence intervals. The mean values of estimated frequency response of $L(s)$ are almost identical for tracking both sum-of-sines and single sines.
- We can see that $L(s)$ falls into the category of McRuer's crossover model. The crossover frequency is about 0.3 to 0.4 Hz and the phase is about 135 degrees. The high gain of $L(s)$ (about 20 dB) at low frequencies (up to 0.1 Hz) implies a small value of $S(s)$ and also implies that $T(s) \approx 1$ (good pursuit tracking performance).



- The estimated frequency responses of $H_{ur}(s)P(s)$ show that in tracking sine waves, $H_{ur}(s)P(s)$ is close to 1 over the range of 0.06 to 0.7 Hz while $H_{ur}(s)P(s)$ is not close to 1 in tracking sum-of-sines signals. In other words, if the signal is a single sine wave, human feedforward controller can generate the proper control signal $u(t)$ based on the model of $P(s)$ and prediction of $r(t)$ to invert the plant. If the signal is a sum-of-sines wave, human operators lose the ability to predict the reference signal and cannot use feedforward control to generate the proper $u(t)$.



Future Work

- We will extend our analysis to more complex plant dynamics such as integrators with time delays .
- We will study how haptic feedback affects the estimated controllers.