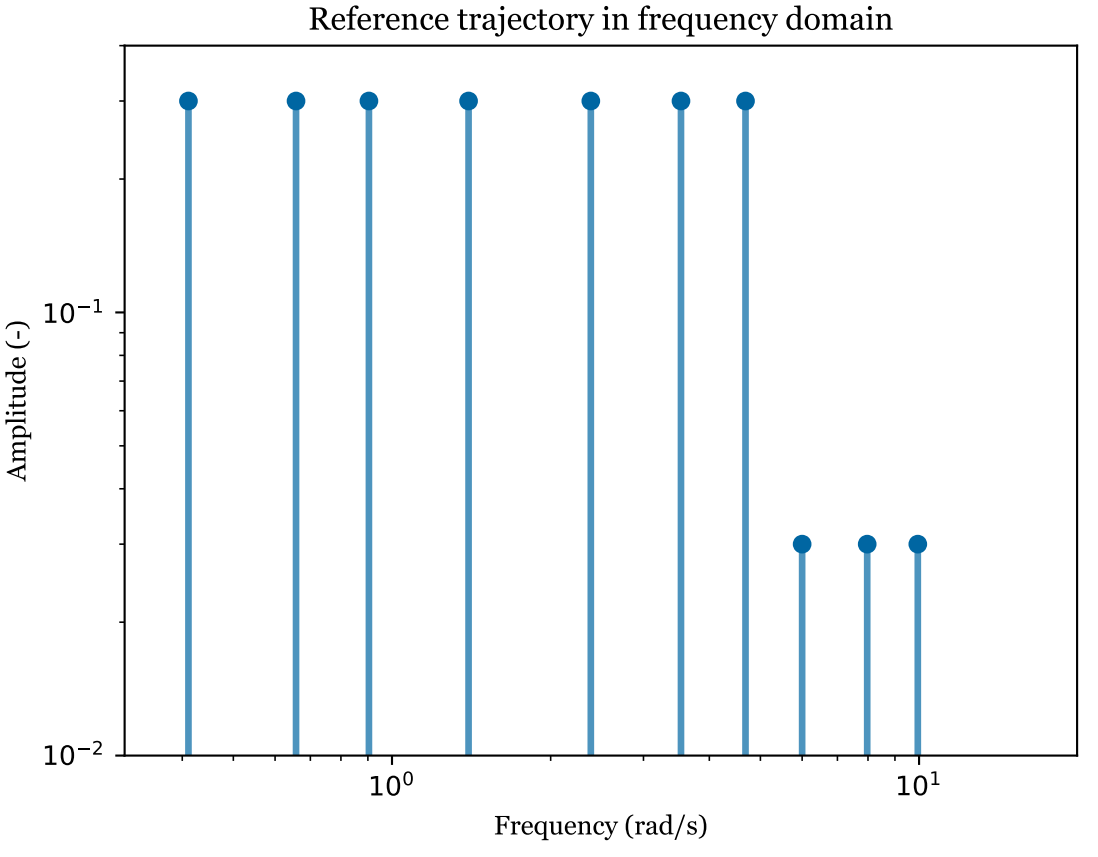
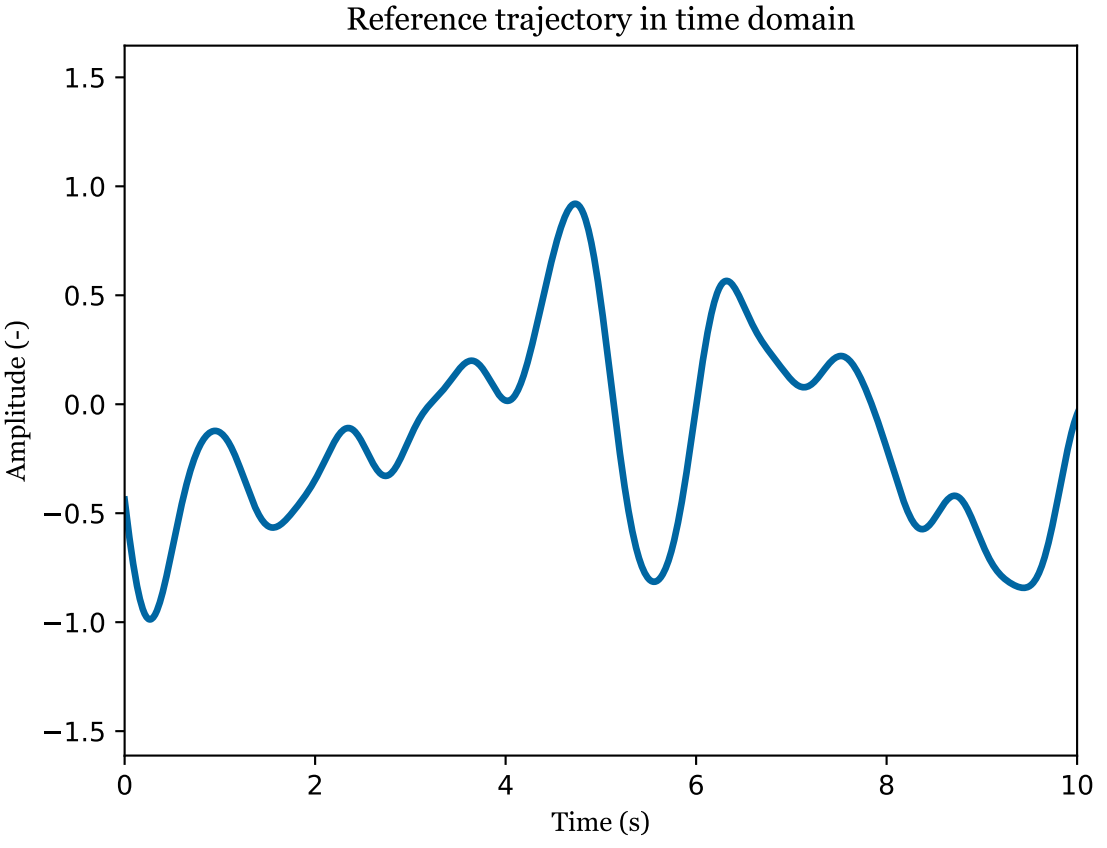
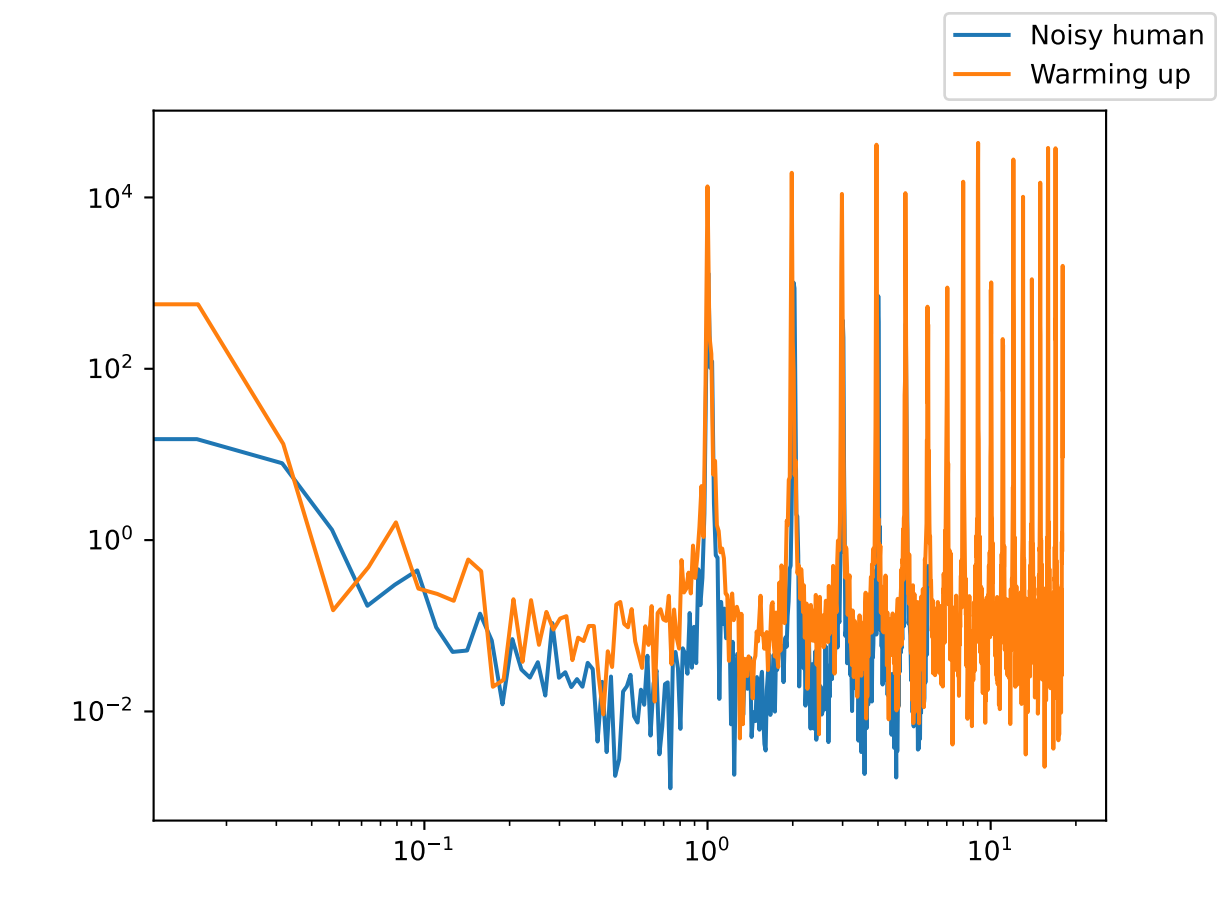
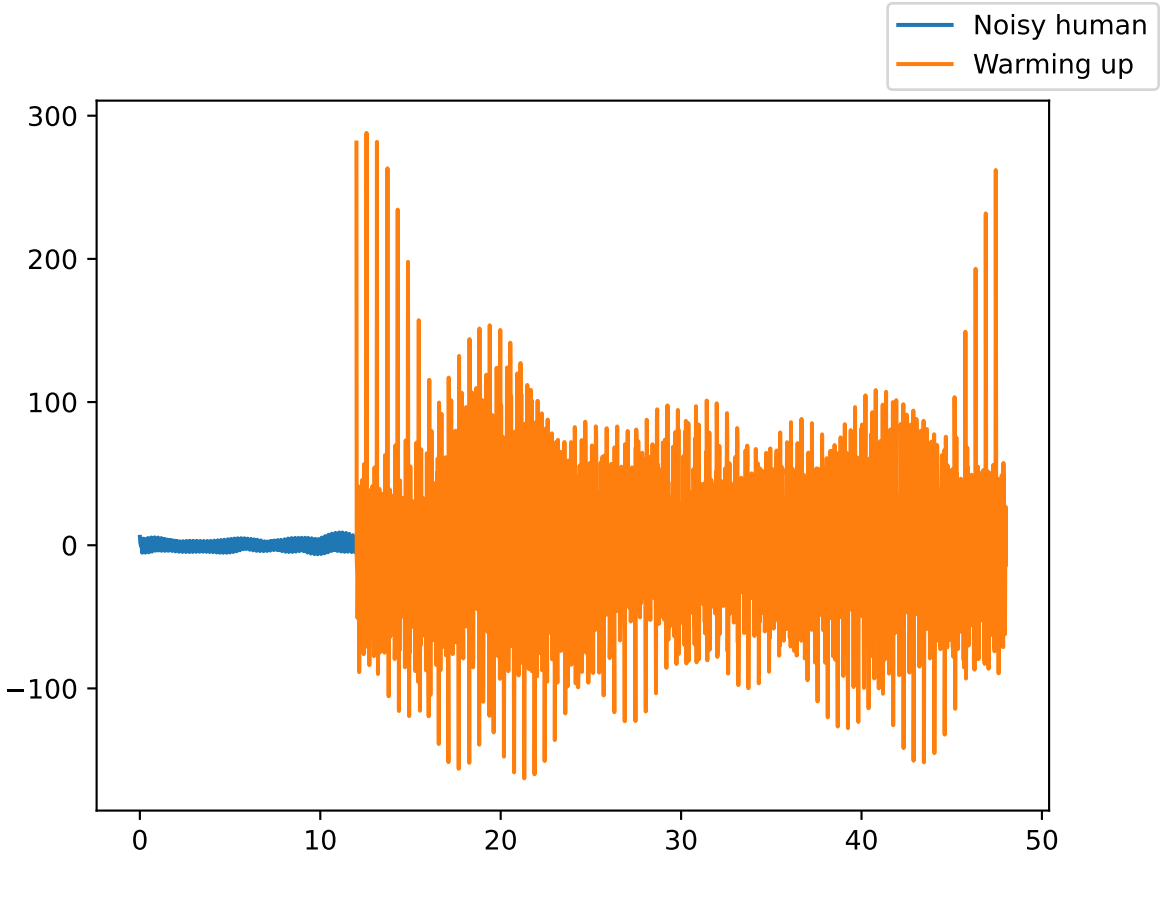
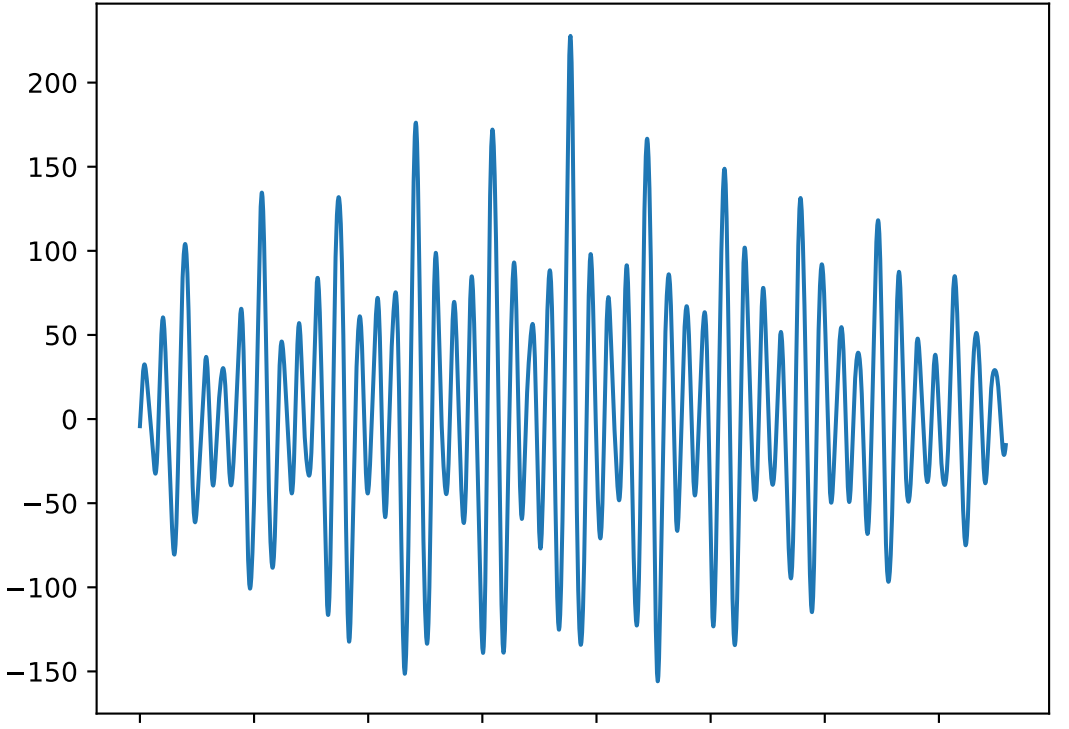
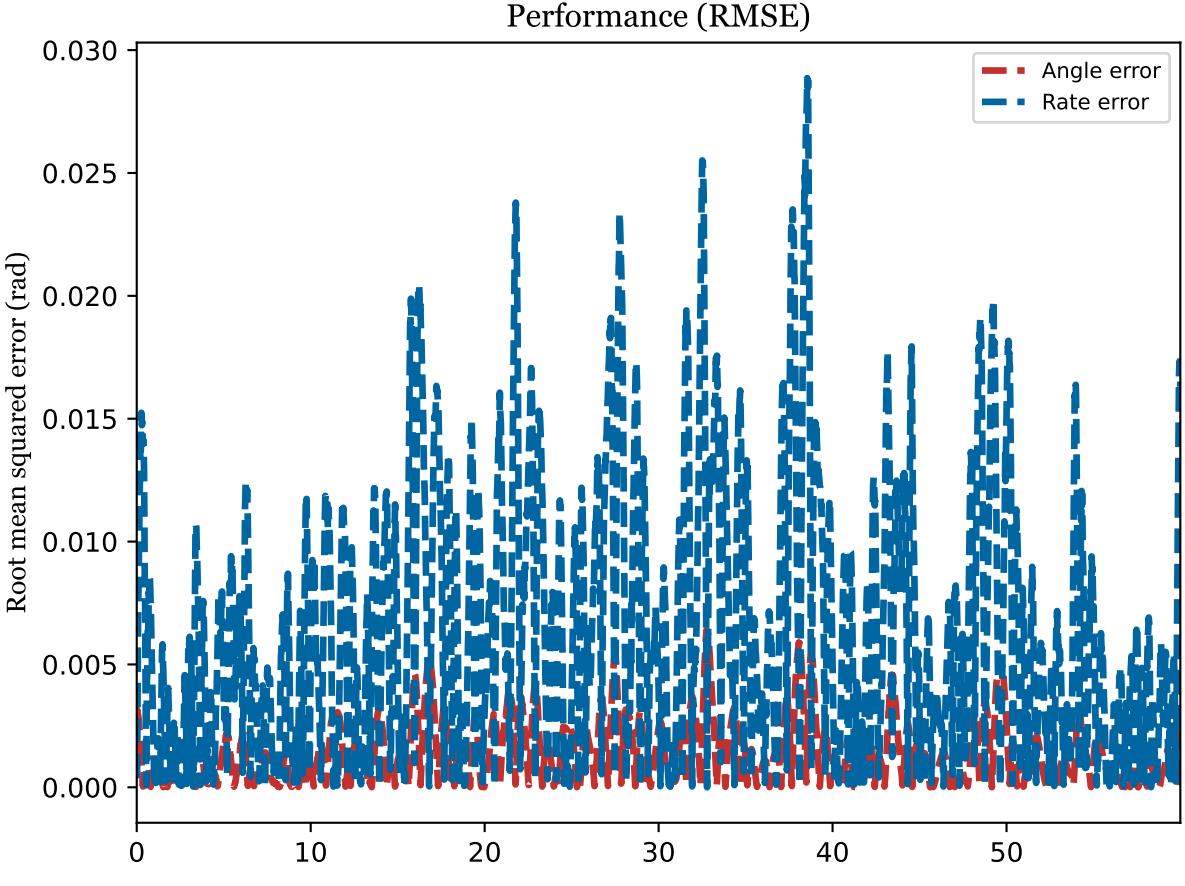

Reference trajectory in frequency domain
Amplitude (-)
10^{-1}
10^{-2}
10^{0}
10^{1}
Frequency (rad/s)

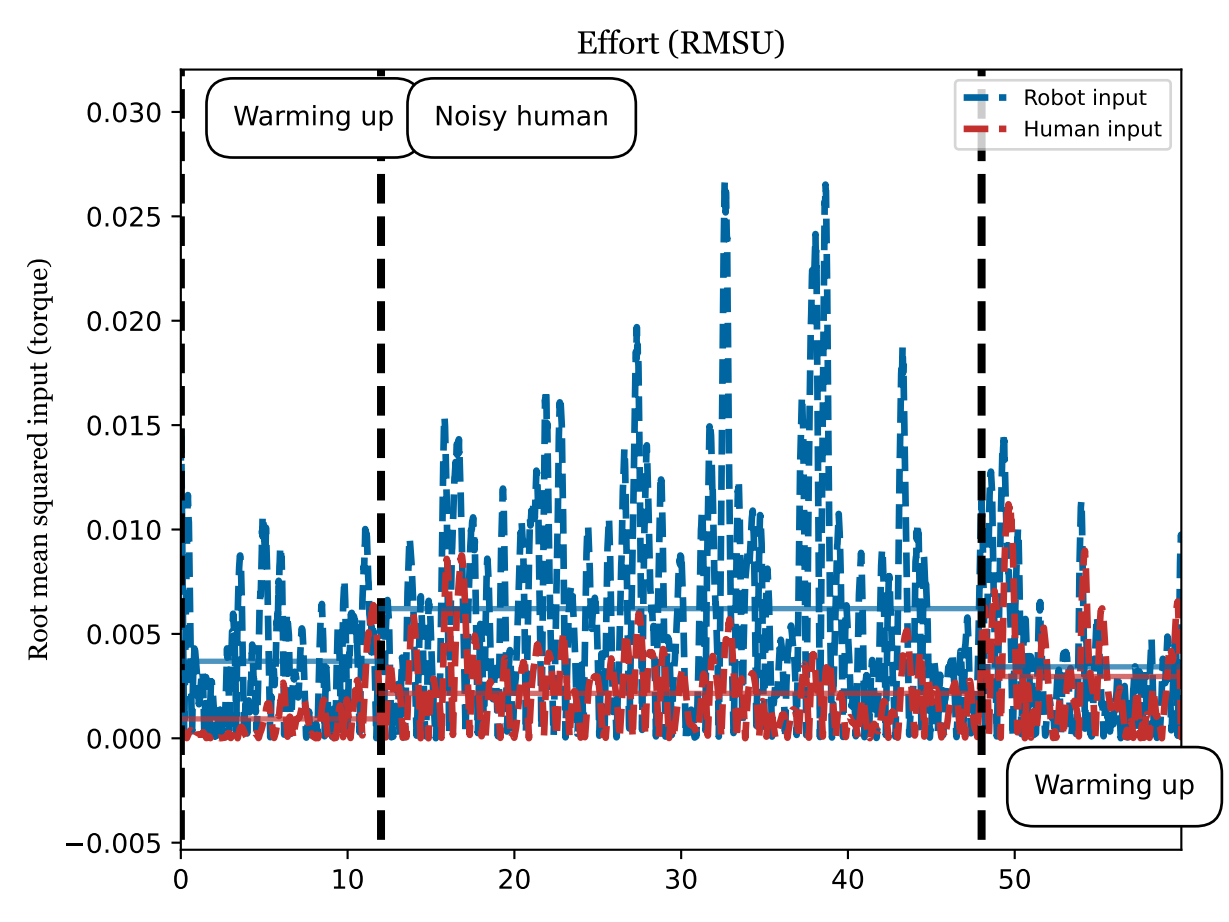

Reference trajectory in time domain
Amplitude (-)
Time (s)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0
2
4
6
8
10

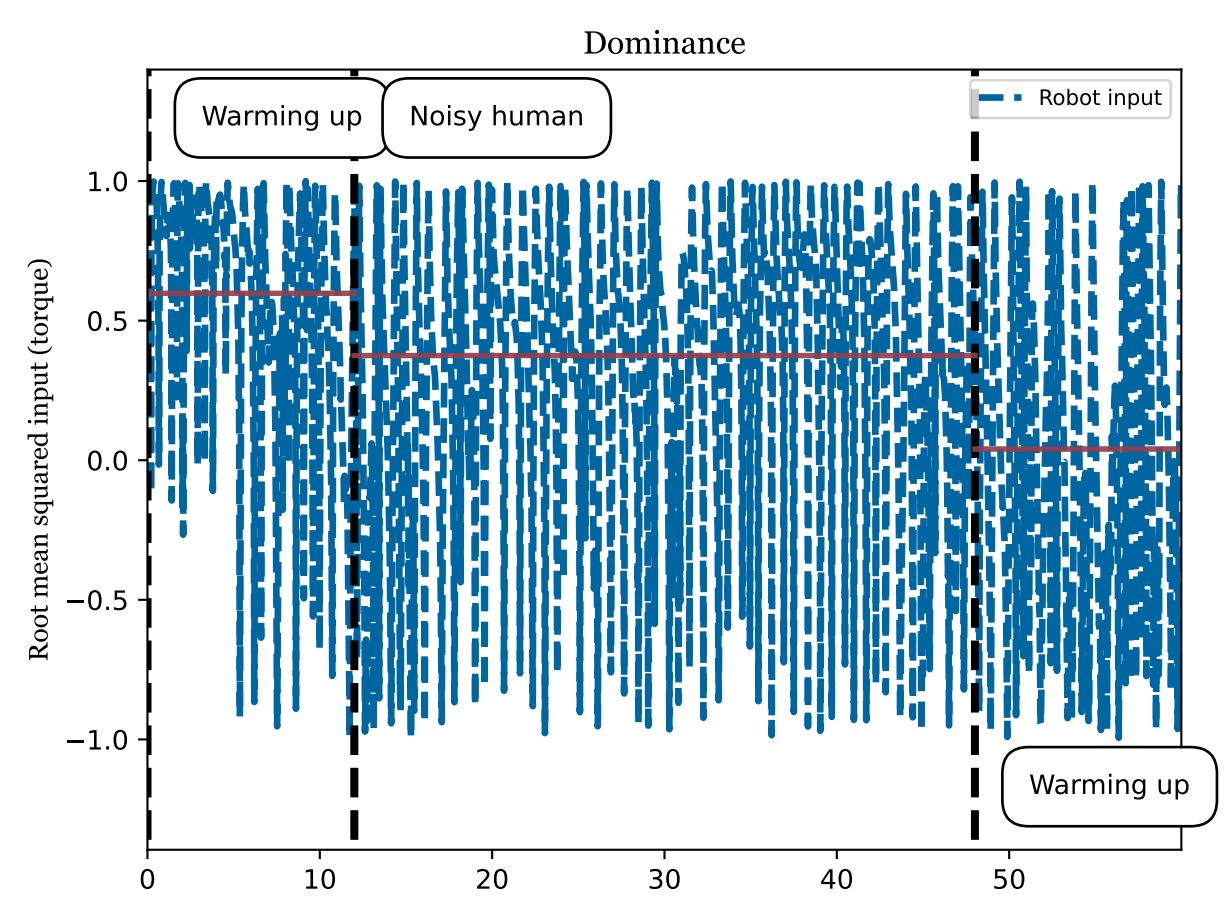

Noisy human
Warming up
10^4
10^2
10^0
10^{-2}
10^{-1}
10^0
10^1

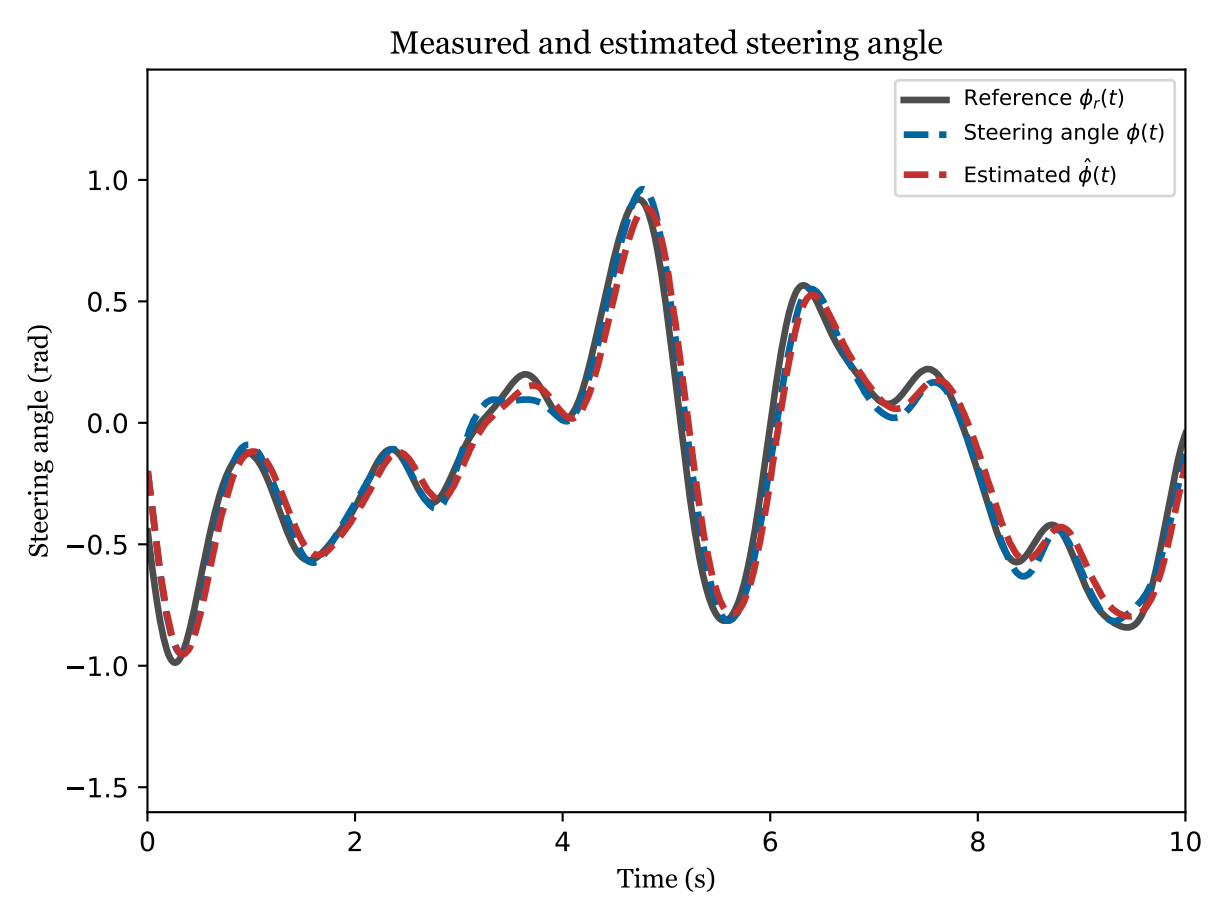

Noisy human
Warming up
300
200
100
0
−100
0
10
20
30
40
50

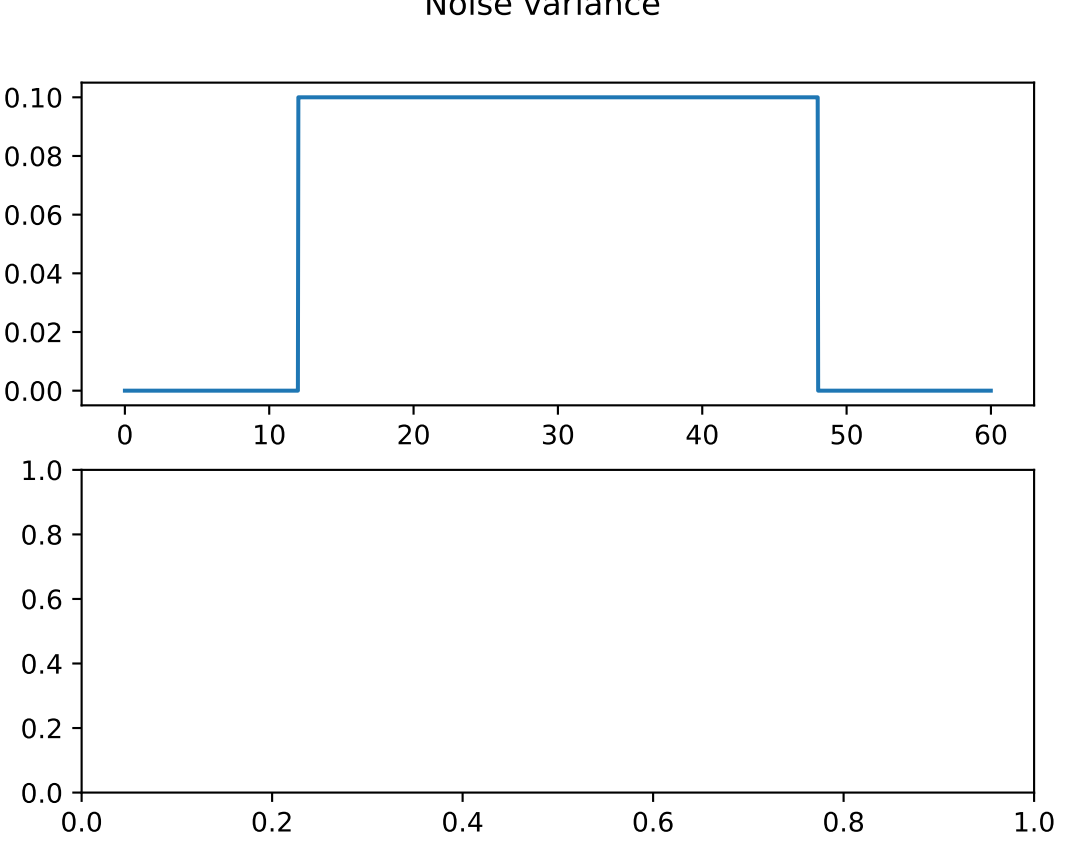

200
150
100
50
0
−50
−100
−150
0
500
1000
1500
2000
2500
3000
3500

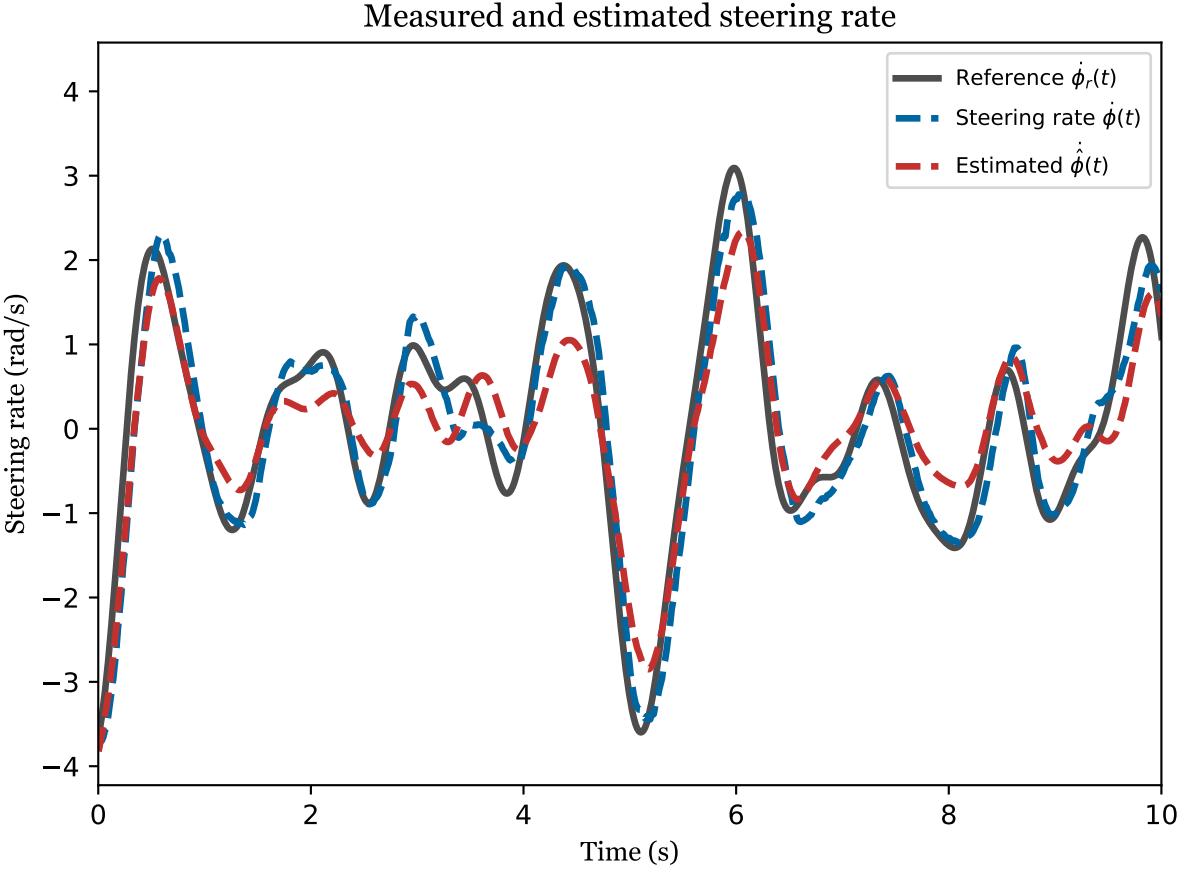

Performance (RMSE)
Angle error
Rate error
Root mean squared error (rad)
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
10
20
30
40
50

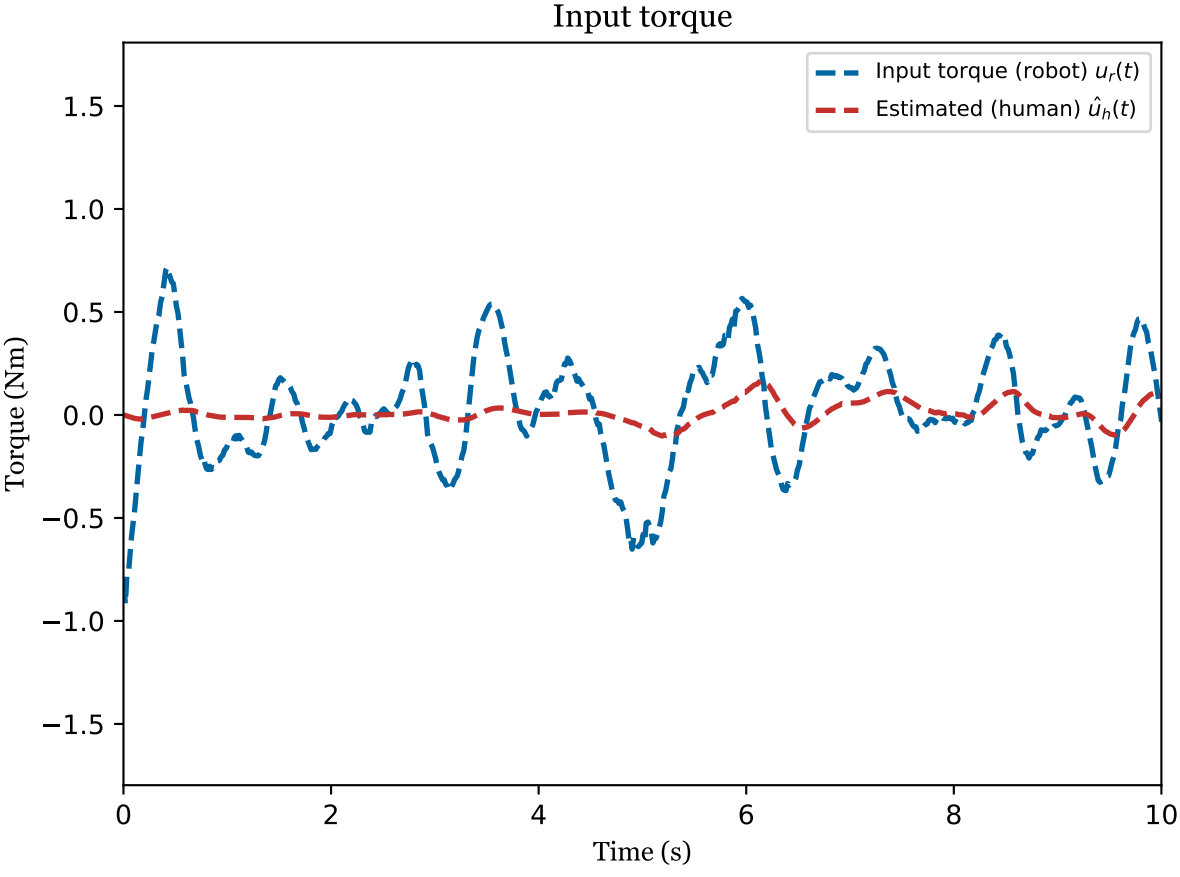

Effort (RMSU)
Warming up
Noisy human
Warming up
Robot input
Human input
Root mean squared input (torque)
0.030
0.025
0.020
0.015
0.010
0.005
0.000
−0.005
0
10
20
30
40
50

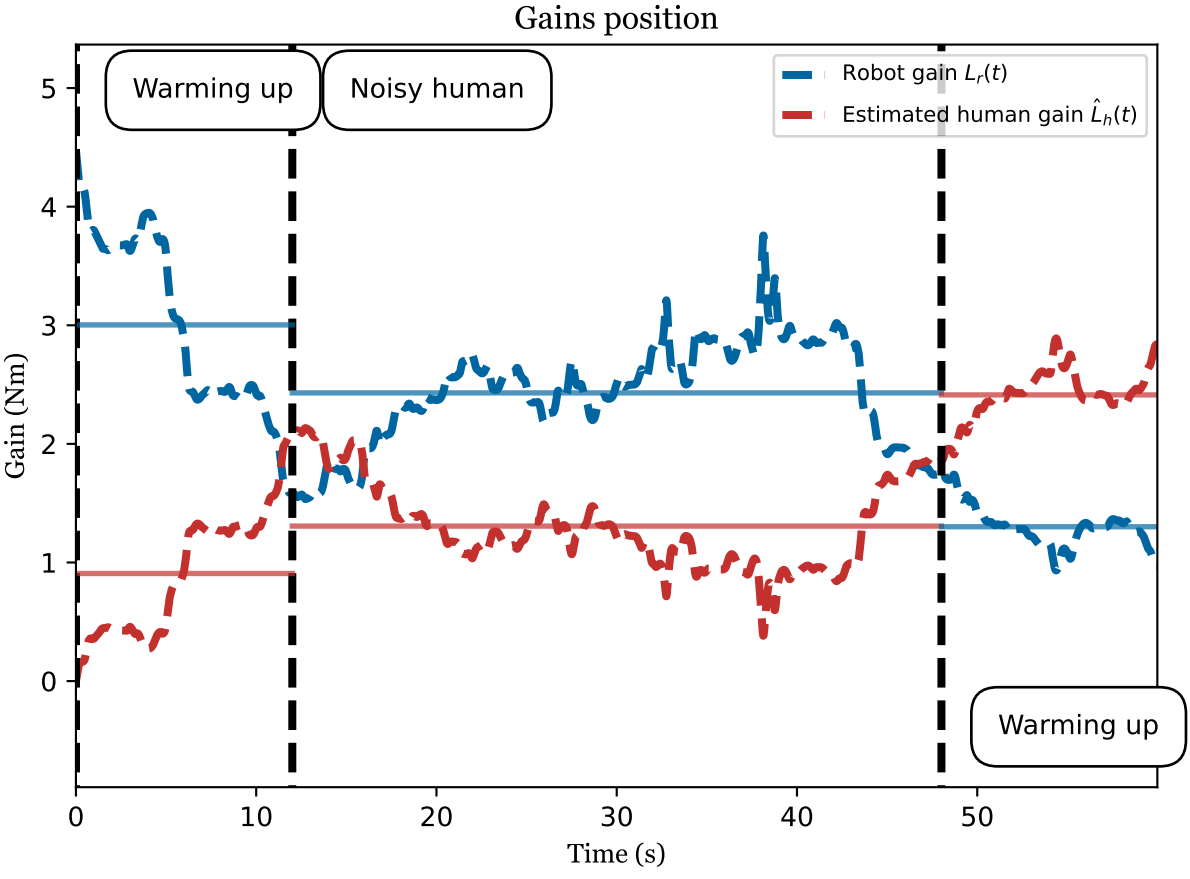

Dominance
Warming up
Noisy human
Warming up
Robot input
Root mean squared input (torque)
1.0
0.5
0.0
−0.5
−1.0
0
10
20
30
40
50

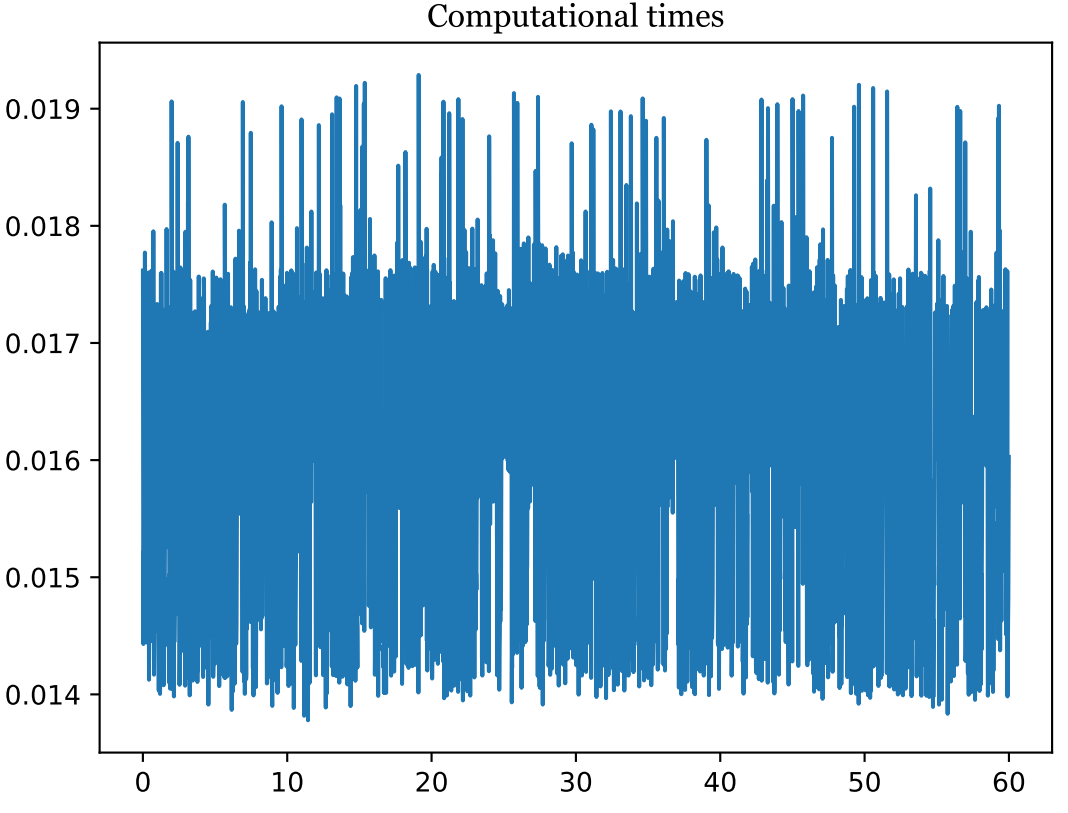

Measured and estimated steering angle
Reference $\phi_r(t)$
Steering angle $\phi(t)$
Estimated $\hat{\phi}(t)$
Steering angle (rad)
1.0
0.5
0.0
−0.5
−1.0
−1.5
0
2
4
6
8
10
Time (s)

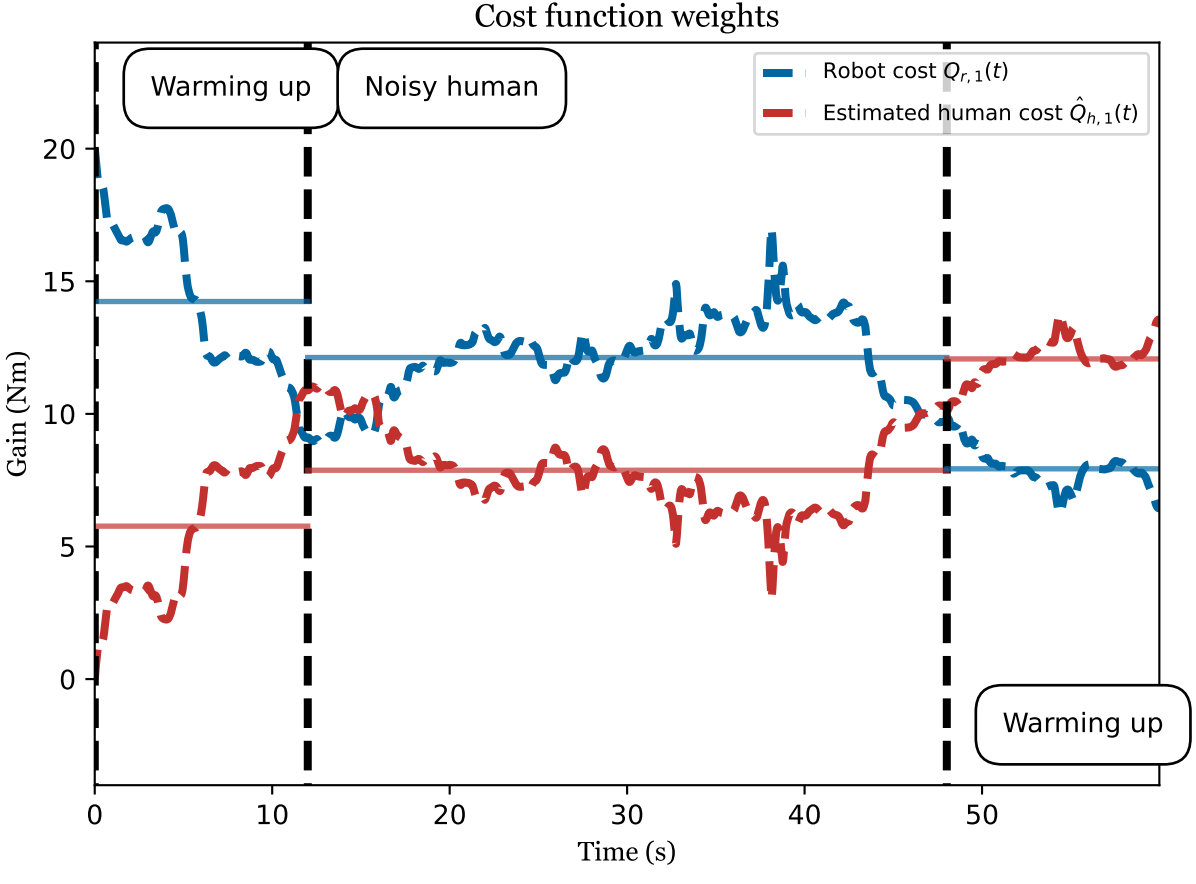

Noise variance
0.10
0.08
0.06
0.04
0.02
0.00
0
10
20
30
40
50
60
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0

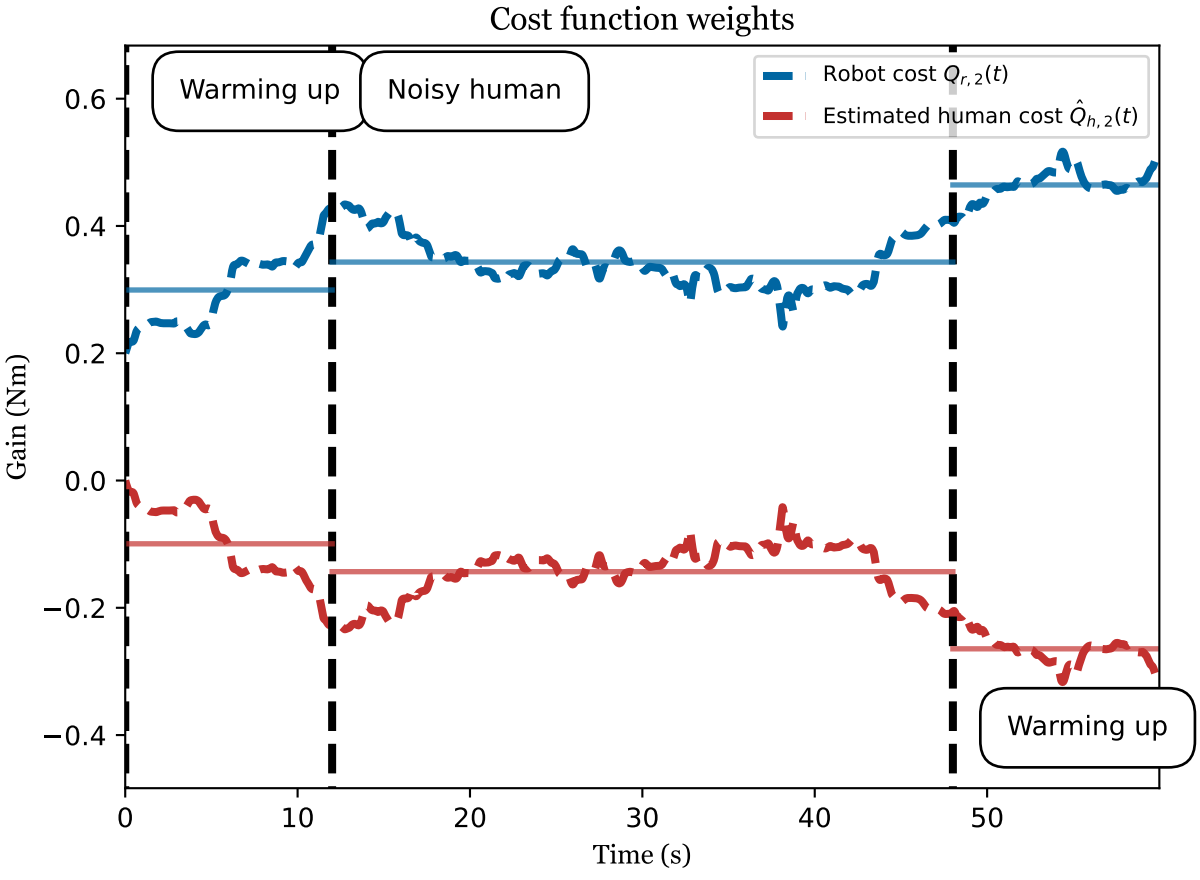

Measured and estimated steering rate
Reference $\dot{\phi}_r(t)$
Steering rate $\dot{\phi}(t)$
Estimated $\hat{\dot{\phi}}(t)$
Steering rate (rad/s)
Time (s)
4
3
2
1
0
−1
−2
−3
−4
0
2
4
6
8
10


Input torque
Input torque (robot) $u_r(t)$
Estimated (human) $\hat{u}_h(t)$
Torque (Nm)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0
2
4
6
8
10
Time (s)


Gains position
Warming up
Noisy human
Warming up
Robot gain $L_r(t)$
Estimated human gain $\hat{L}_h(t)$
Gain (Nm)
Time (s)
0
1
2
3
4
5
0
10
20
30
40
50


Computational times
0.019
0.018
0.017
0.016
0.015
0.014
0
10
20
30
40
50
60


Cost function weights
Warming up
Noisy human
Warming up
Robot cost $Q_{r,1}(t)$
Estimated human cost $\hat{Q}_{h,1}(t)$
Gain (Nm)
Time (s)
0
5
10
15
20
0
10
20
30
40
50


Cost function weights
Warming up
Noisy human
Robot cost $Q_{r,2}(t)$
Estimated human cost $\hat{Q}_{h,2}(t)$
Warming up
Gain (Nm)
Time (s)
0.6
0.4
0.2
0.0
−0.2
−0.4
0
10
20
30
40
50