# Internet-based Force-reflecting Telerobotic Systems

Presented by:

Jared B Jensen
February 7, 2002

Utah State University
ECE 7750

# Reference

Oboe, R. and Fiorini, P. A Design and Control Environment for Internet-Based Telerobotics. The International Journal of Robotics Research. Vol. 17, No. 4, pp. 433-449, 1998.

# Introduction

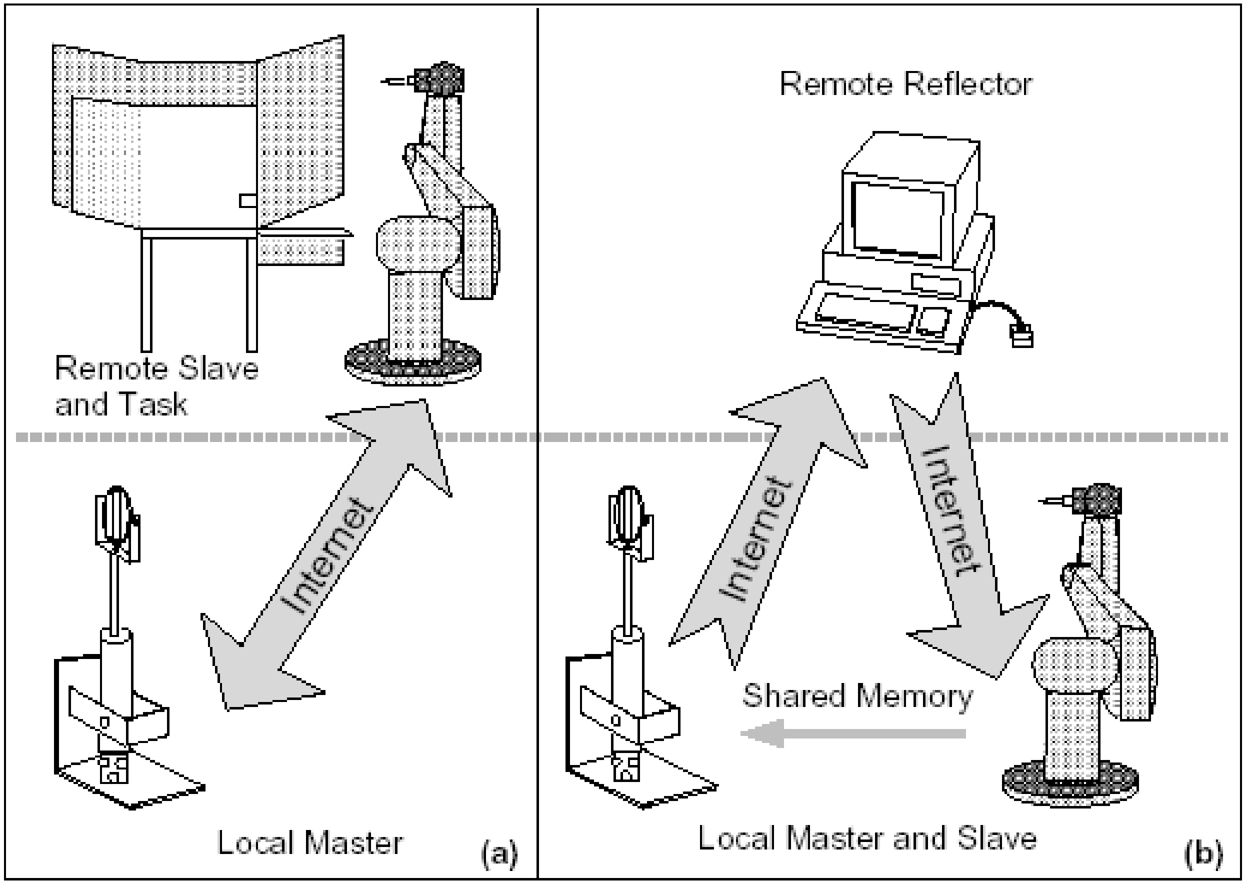
What is a Telerobotic System?

A system where a remote “robot” slave is connected to a local “robot” master through a segment of the Internet. (Shown on next slide)

What does Force-reflecting mean?

The operator of the local robot can feel the forces applied by the remote robot to its environment.

# A typical structure of Internet-based telerobotics.



## Key Issues

Internet data has variable time delay and packet losses which depend on the characteristics of the network and on its load.

The delay depends on:

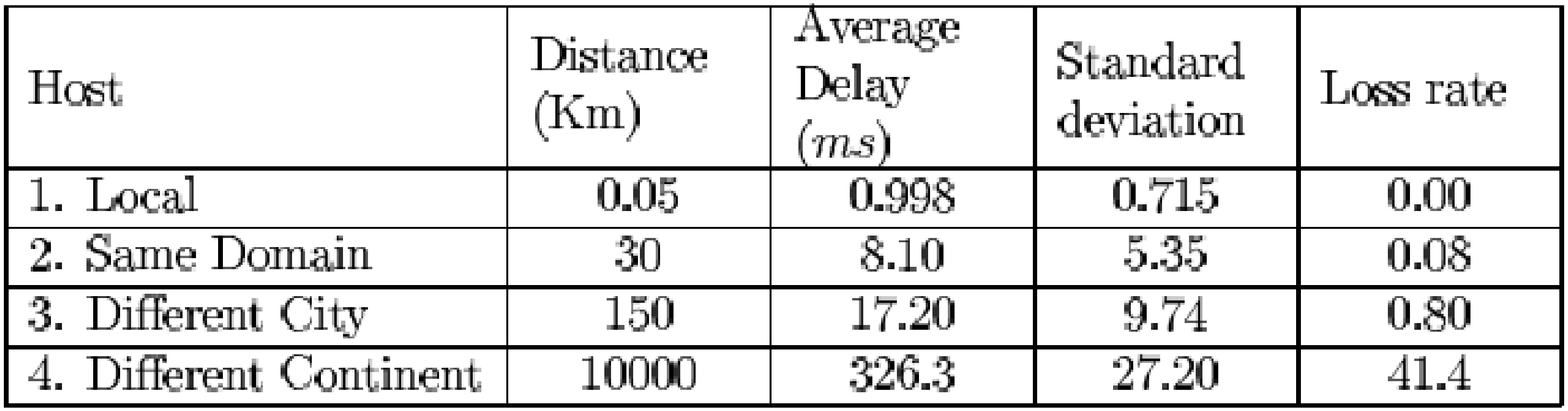
- Packet route
- Handling policies (protocol) used at each node
- Network congestion

This variable delay makes it very difficult to determine an exact analytical model of an Internet connection.

# Approximate Internet Model

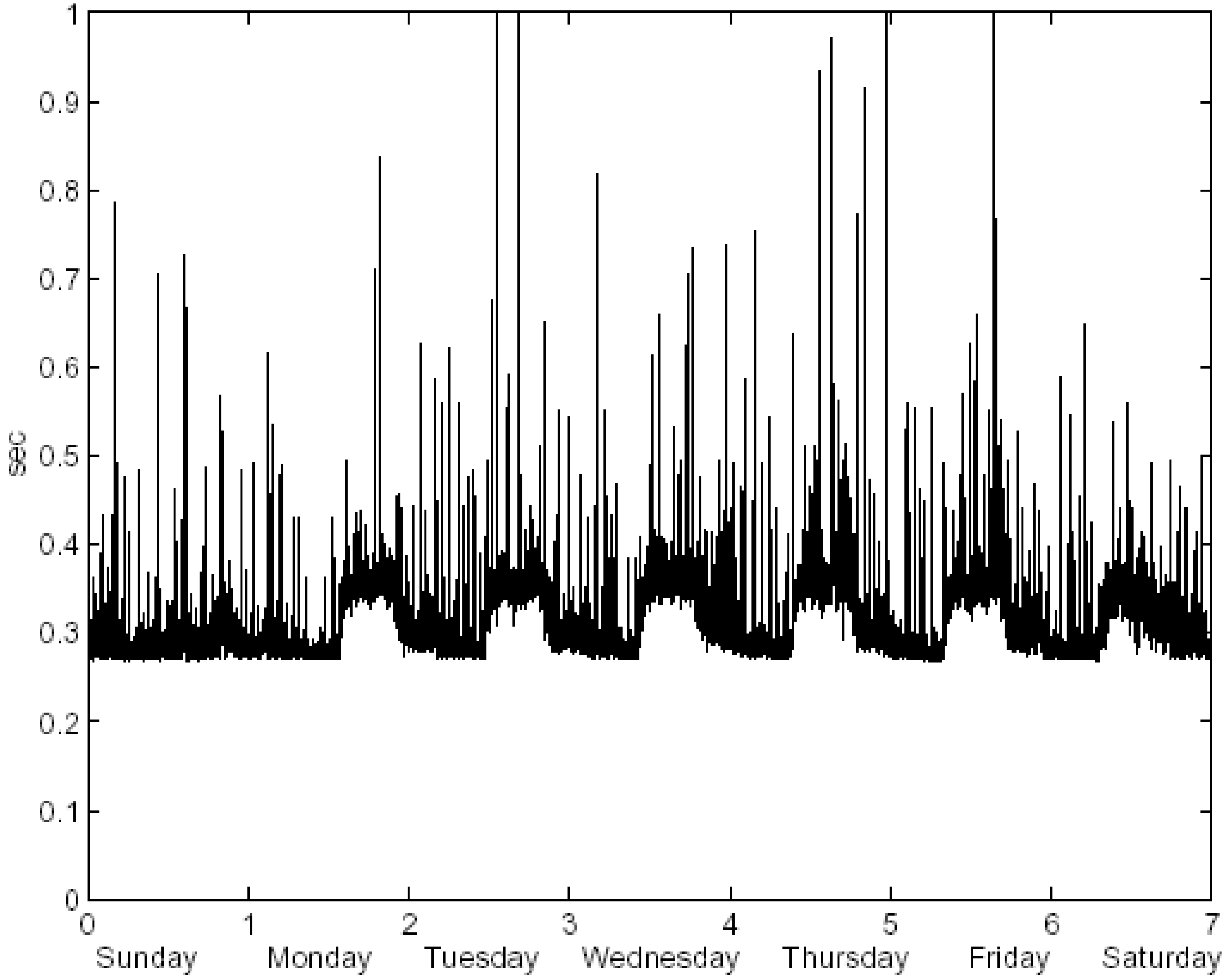
Use the Internet Control Message Protocol (ICMP) to measure the round trip time (RTT) of probing packets sent to the remote telerobot.

- Packet rates of 10 to 100 ms
- 100 ms probes
- 1000 second measurement

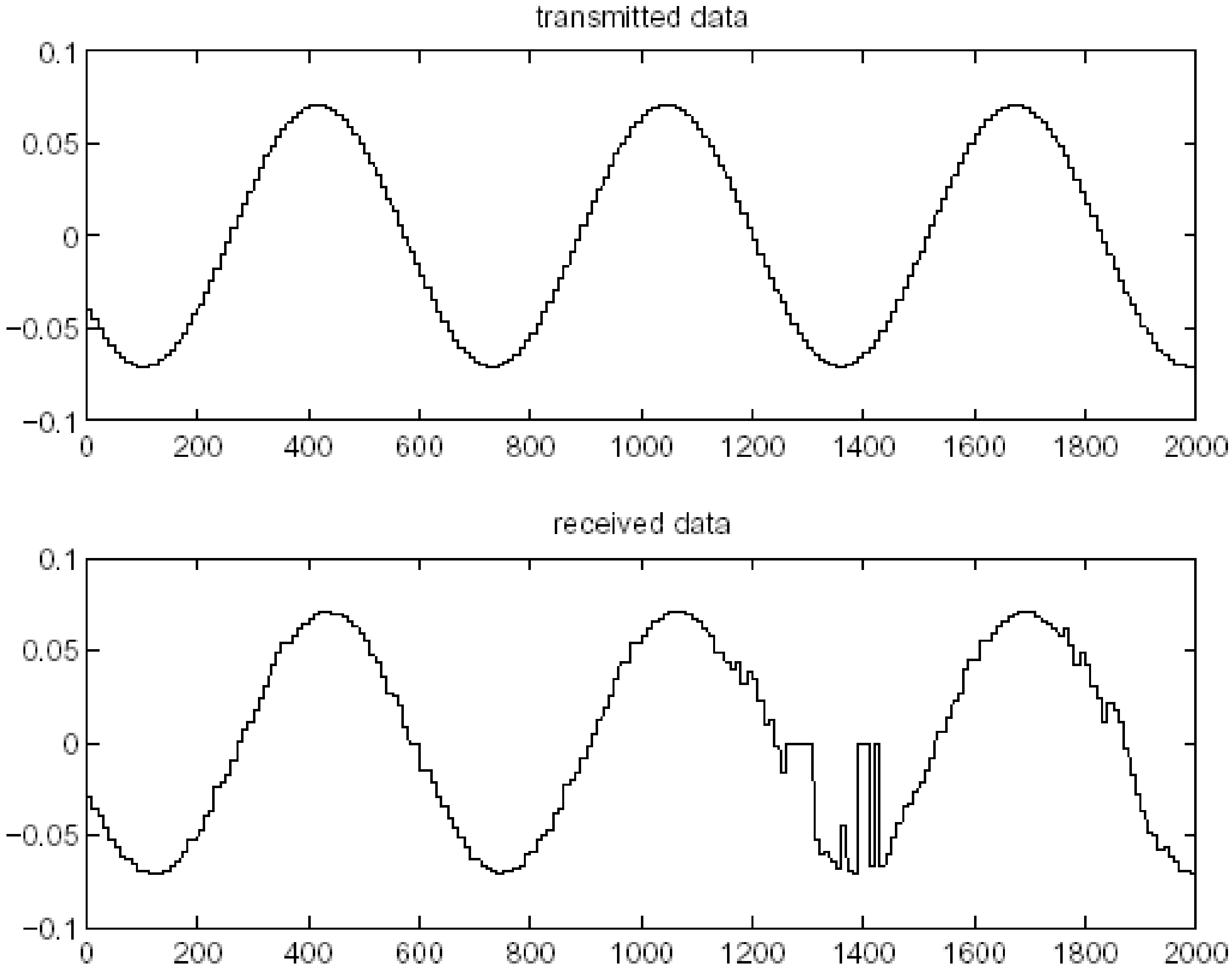


| Host | Distance (Km) | Average Delay ($ms$) | Standard deviation | Loss rate |
|---|---|---|---|---|
| 1. Local | 0.05 | 0.998 | 0.715 | 0.00 |
| 2. Same Domain | 30 | 8.10 | 5.35 | 0.08 |
| 3. Different City | 150 | 17.20 | 9.74 | 0.80 |
| 4. Different Continent | 10000 | 326.3 | 27.20 | 41.4 |

The average delay depends on the network load and shows daily and weekly variations as shown below.

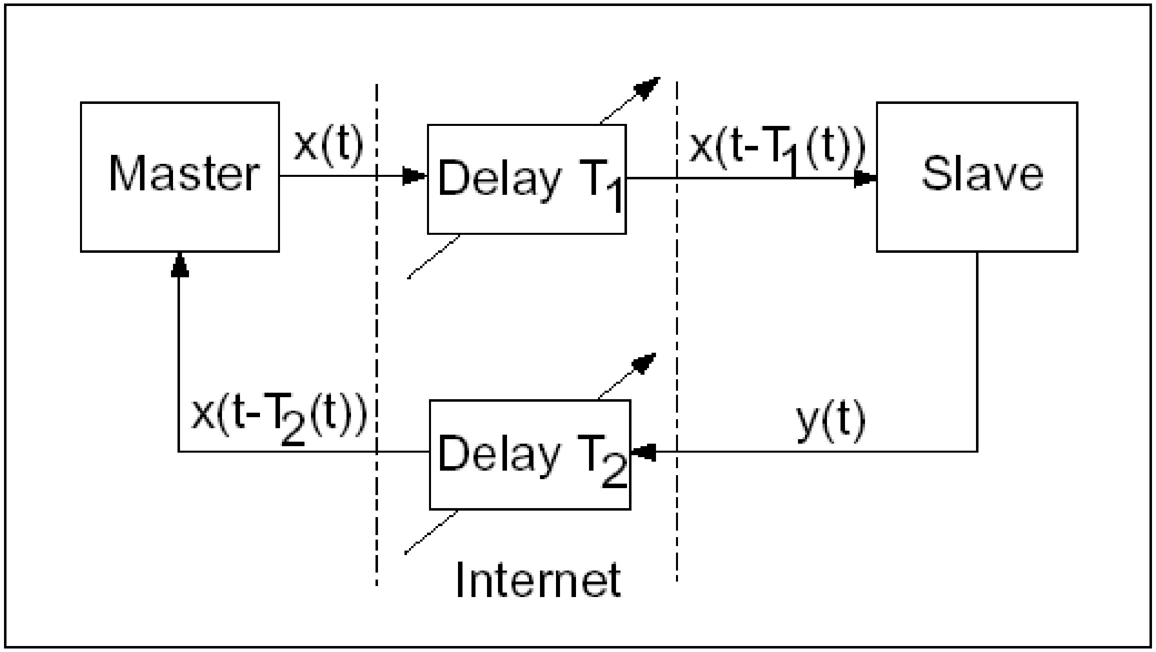


A test waveform sent over a 150 Km Internet segment and measured at the remote node is shown below.



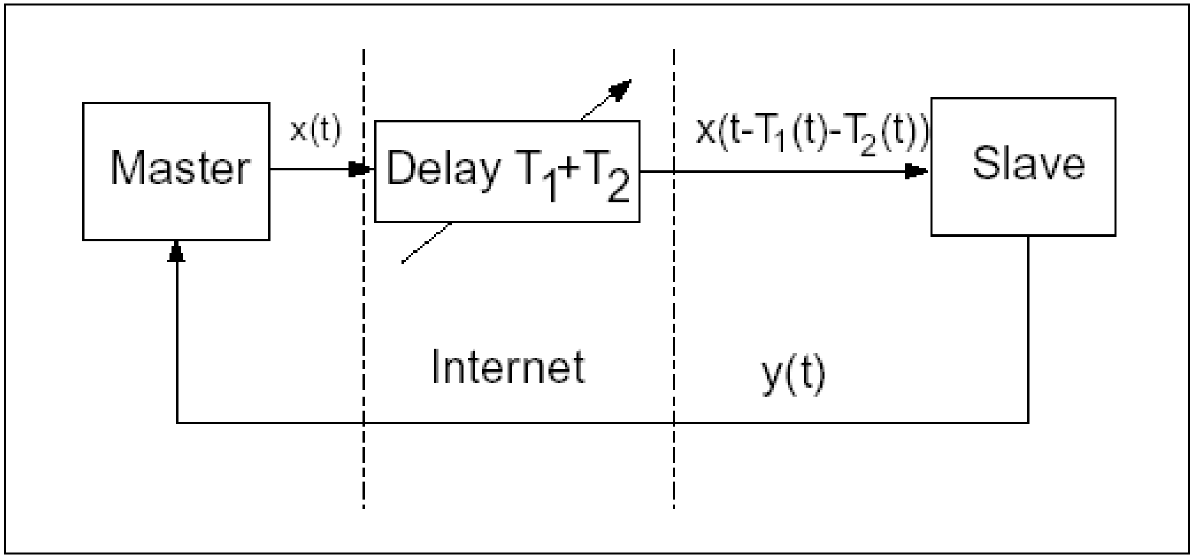
# Controller Design

The forward and the feedback data paths are characterized by different delays, $T_1(t)$ and $T_2(t)$ with $RTT(t) = T_1(t) + T_2(t)$ and by different packet losses.



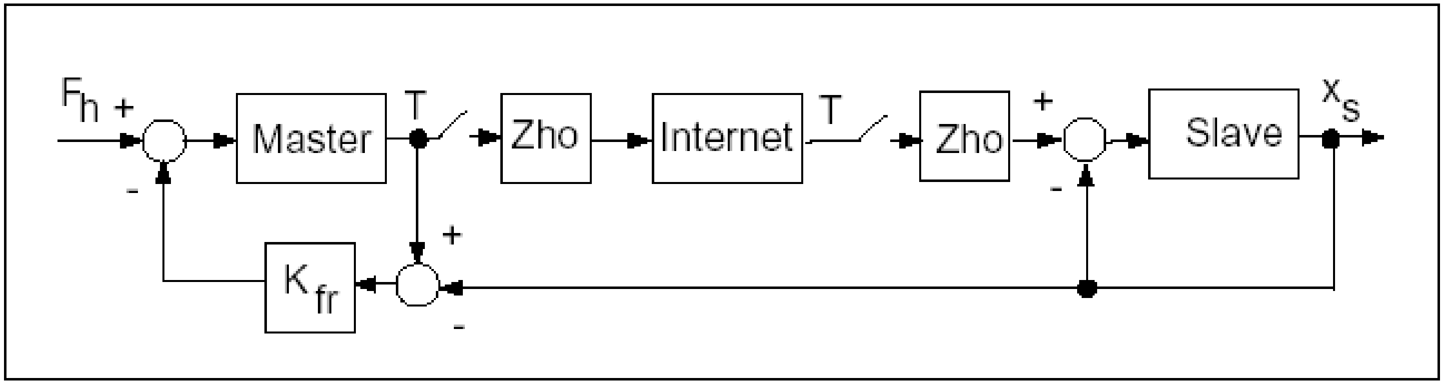
Assumptions:

- Master and Slave are linearized by suitable controllers.
- Both data paths are routed through the same Internet segment. RTT(*t*) = *h*(*t*)
- Packet losses are equally distributed on each segment.

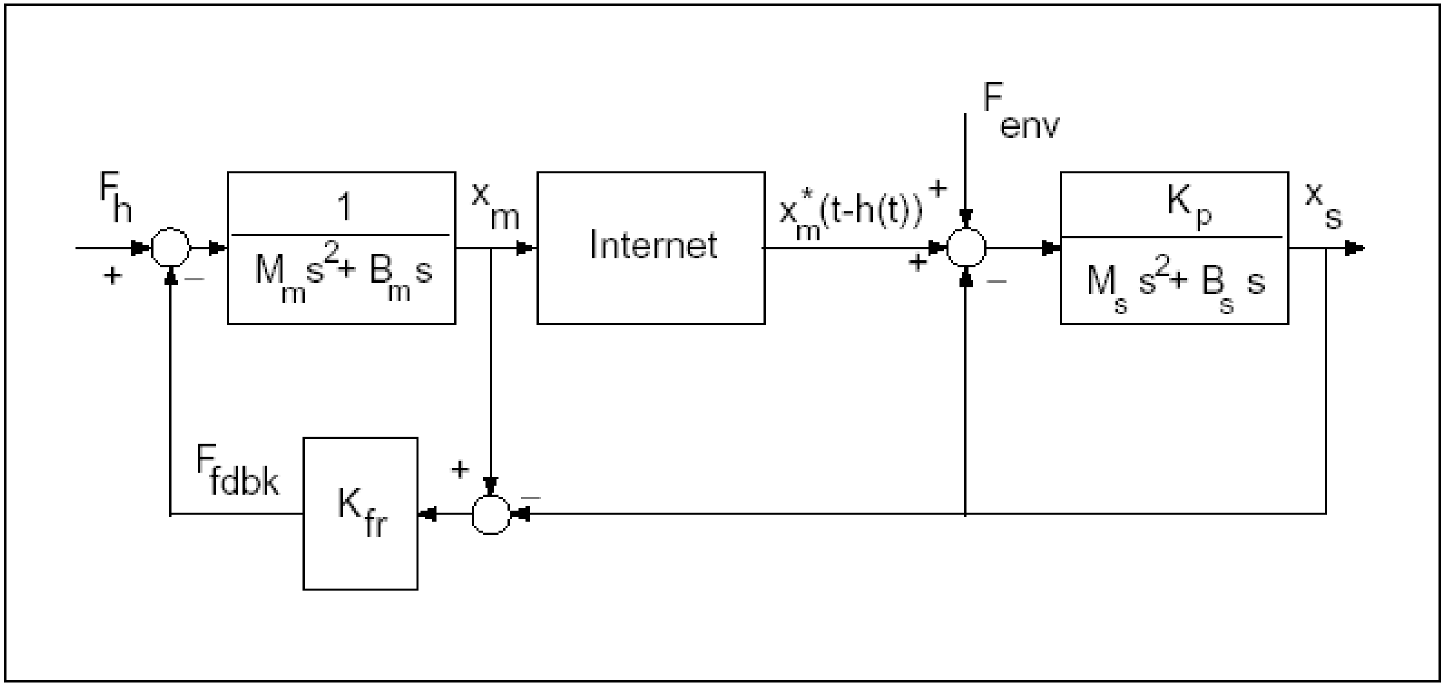


The model must also include the influence of the discrete data communication.

Packets are initially synchronized to the controller cycle time. However, due to the variable time-delay introduced by the Internet segment and by the lack of synchronization between the real-time computer and the reflector, the received packets arrive randomly w.r.t. the control cycle.



For the actual controller design, the standard position-based force feedback scheme shown below is considered.



A new decentralized controller based on state variable feedback is proposed.

The forces acting on the master are proportional to the difference between the position of the master and the slave.

Consider a single dof system with the following state-space equations:

$$\begin{aligned}\Sigma_1 &: \dot{x}_1 = A_1 x_1(t) + B_1 u_1(t) + A_{21} x_2(t - h(t)) \\ \Sigma_2 &: \dot{x}_2 = A_2 x_2(t) + B_2 u_2(t) + A_{12} x_1(t - h(t))\end{aligned}$$

$h(t) = (T_1(t) + T_2(t))/2$

$\Sigma_1$ and $\Sigma_2$ represent the master and the slave.

$x_1$ and $x_2$ represent the full state of master and slave.

The matrix coefficients of the state equations are given by:

$$A_1 = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{B_m}{M_m} \end{bmatrix};\ B_1 = \begin{bmatrix} 0 \\ \frac{1}{M_m} \end{bmatrix};\ A_{21} = \begin{bmatrix} 0 & 0 \\ \frac{K_{fr}}{M_m} & 0 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{B_s}{M_s} \end{bmatrix};\ B_2 = \begin{bmatrix} 0 \\ \frac{1}{M_s} \end{bmatrix};\ A_{12} = \begin{bmatrix} 0 & 0 \\ \frac{K_p}{M_s} & 0 \end{bmatrix}$$

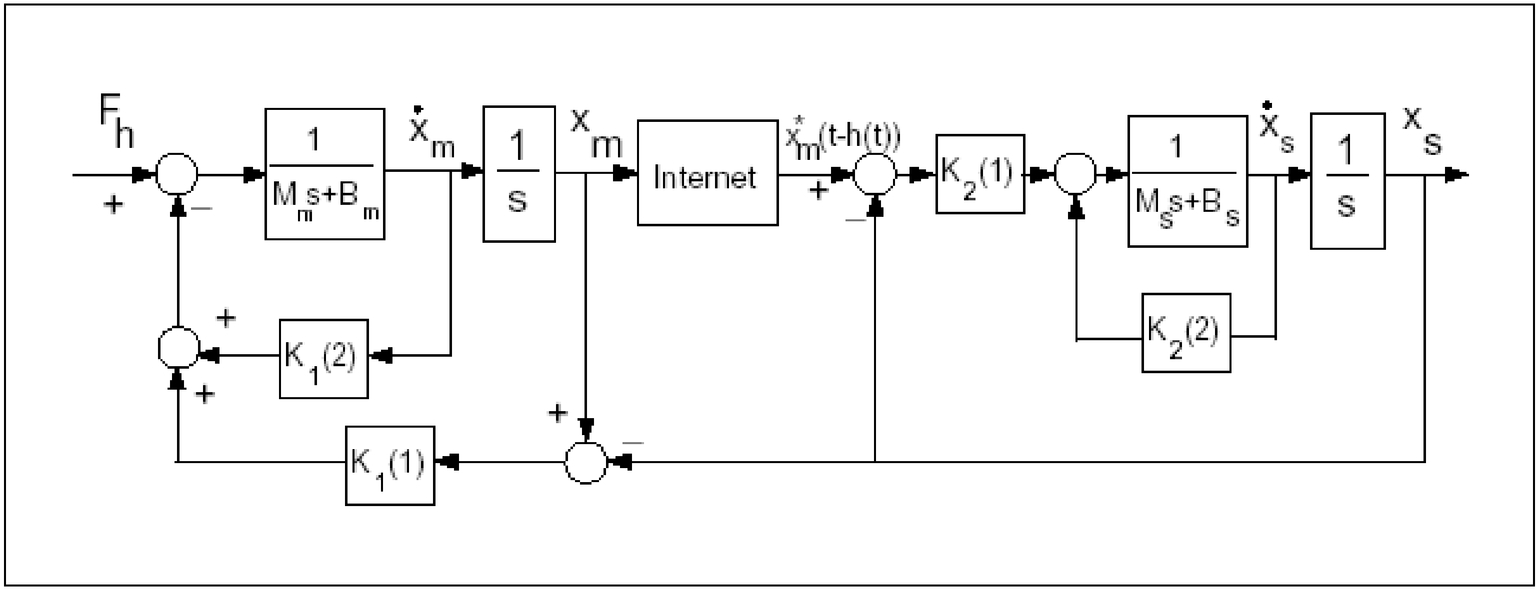
$K_{fr}$ = force feedback gain.
$K_p$ = gain of the slave controller.

$M_m$, $B_m$, $M_s$, $B_s$ = mass and friction coefficients.

The proposed decentralized state feedback controller is given by the following equations:

$$\begin{cases} u_1 & = & K_1 x_1 \\ u_2 & = & K_2 x_2 \end{cases}$$

$K_1 = [K_1(1), K_1(2)]$ and $K_2 = [K_2(1), K_2(2)]$ are two gain vectors shown in the figure below.



Since state feedback ensures correct tracking only when reference and feedback are multiplied by the same gain, it follows that $A_{21}$ and $A_{12}$ depend on the controller gains:

$$A_{21} = \begin{bmatrix} 0 & 0 \\ \frac{K_1(1)}{M_m} & 0 \end{bmatrix}; \quad A_{21} = \begin{bmatrix} 0 & 0 \\ \frac{K_2(1)}{M_s} & 0 \end{bmatrix}$$

Rewrite the state equations including the controller equations:

$$\Sigma : \dot{x}(t) = A_k x(t) + A_d x(t - h(t))$$

The matrix coefficients now become:

$$A_k = \begin{bmatrix} A_1 - B_1 K_1 & 0 \\ 0 & A_2 - B_2 K_2 \end{bmatrix}; \quad A_d = \begin{bmatrix} 0 & A_{21} \\ A_{12} & 0 \end{bmatrix}; \quad x(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix}$$

The computation of the feedback gains is given in the paper. The values of $K_1$ and $K_2$ are:

$$K_1(1) > \frac{\gamma_m - 1}{4} M_m \alpha^2 \qquad (8) \qquad K_2(1) > \frac{\gamma_s - 1}{4} M_s \alpha^2$$

$$K_1(2) > \gamma_m \alpha M_m + \frac{K_1(1)^2}{M_m} - B_m \quad (9) \qquad K_2(2) > \gamma_s \alpha M_s + \frac{K_1(1)^2}{M_s} - B_s$$

where $\alpha = \frac{1}{1-\overline{\tau}}$ , $\dot{h}(t) \leq \overline{\tau} < 1 \quad \forall t$ represents the network performance and $\gamma_m, \gamma_s$ are free design parameters.

# Jitter and Losses Compensation

Delay Jitter affects both the amplitude and frequency of the transmitted data.

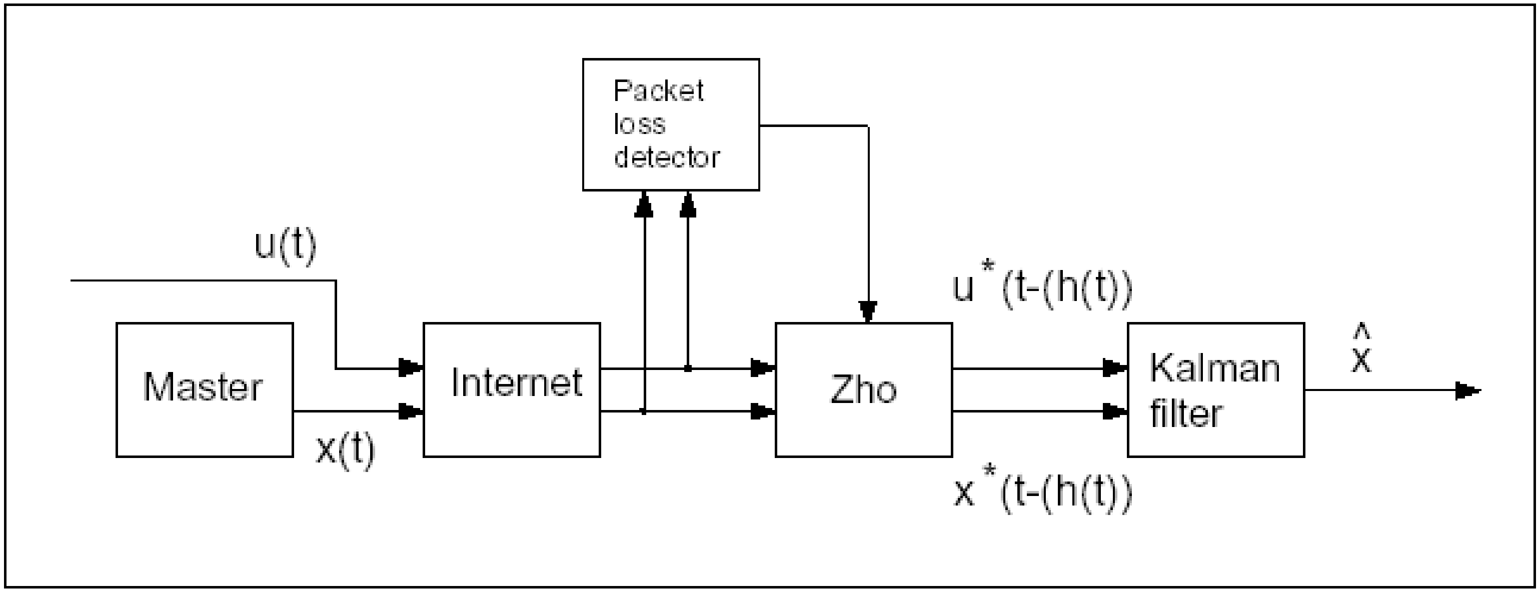
Take advantage of the fact that haptic feedback is bandwidth and amplitude limited by approximating Internet noise with the *worst case* additive noise given by the following relation:

$$\sigma_a = (2\pi BA)^2 \sigma_d$$

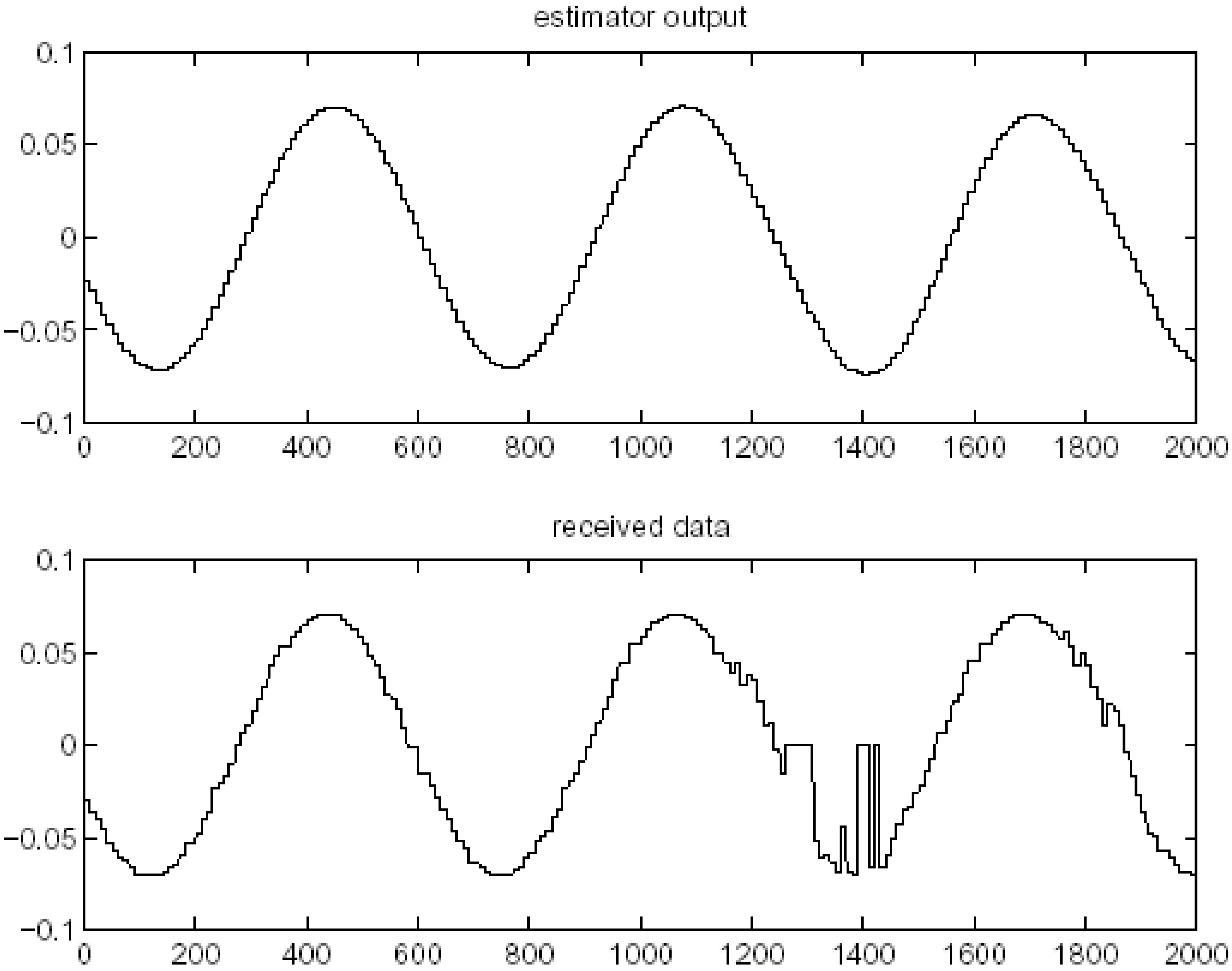
*A* and *B* represent the max. values of the amplitude and frequency and $\sigma_d$ is the variance of the delay computed from the RTT measurements.

Compensate this noise with an optimal filter at the slave side. The filter is an asymptotic Kalman filter, matching the master model and the input/output noise variance of the equation on the last slide.

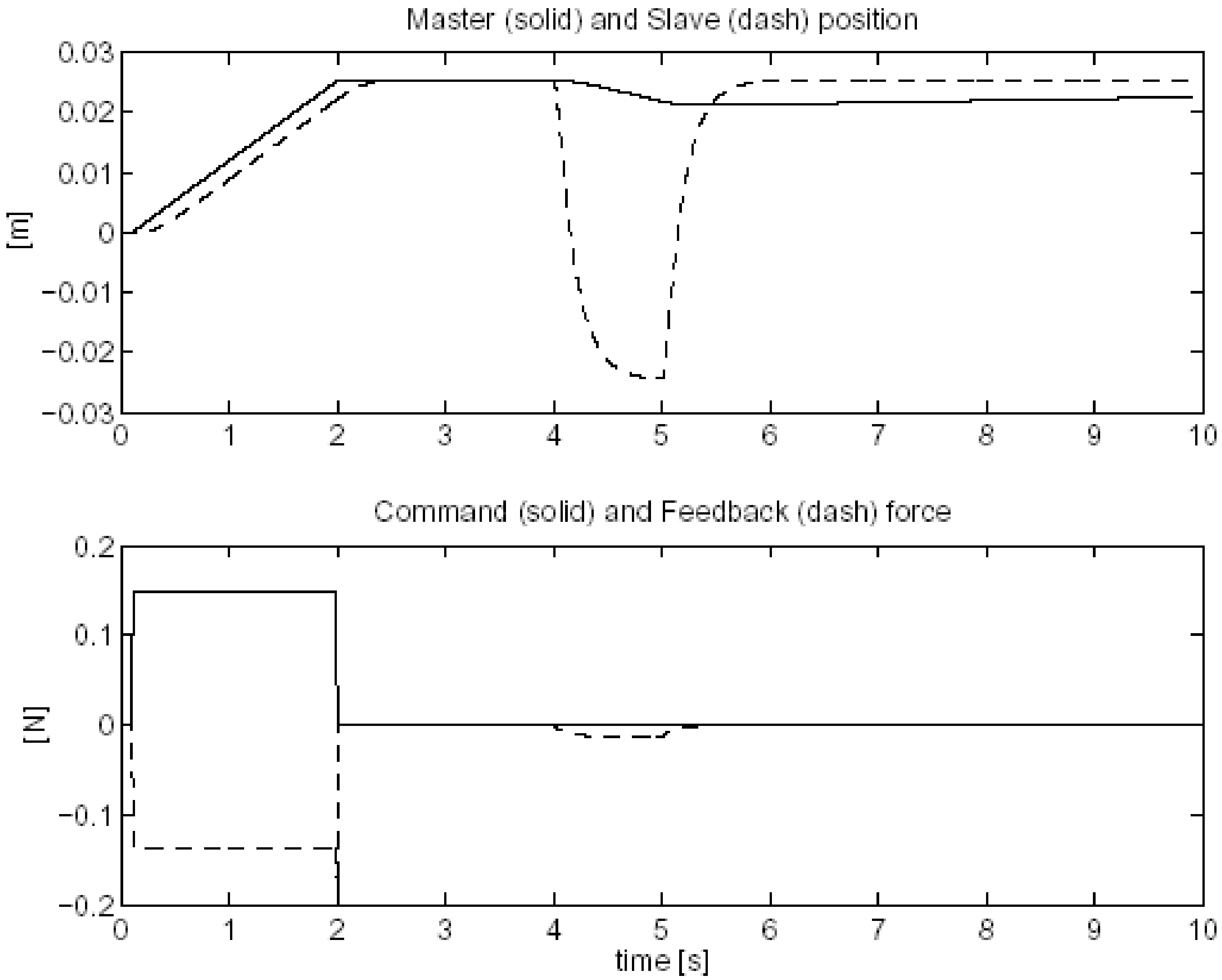
A block diagram of the jitter compensation estimator is shown below.



# Comparison between received and estimated position.

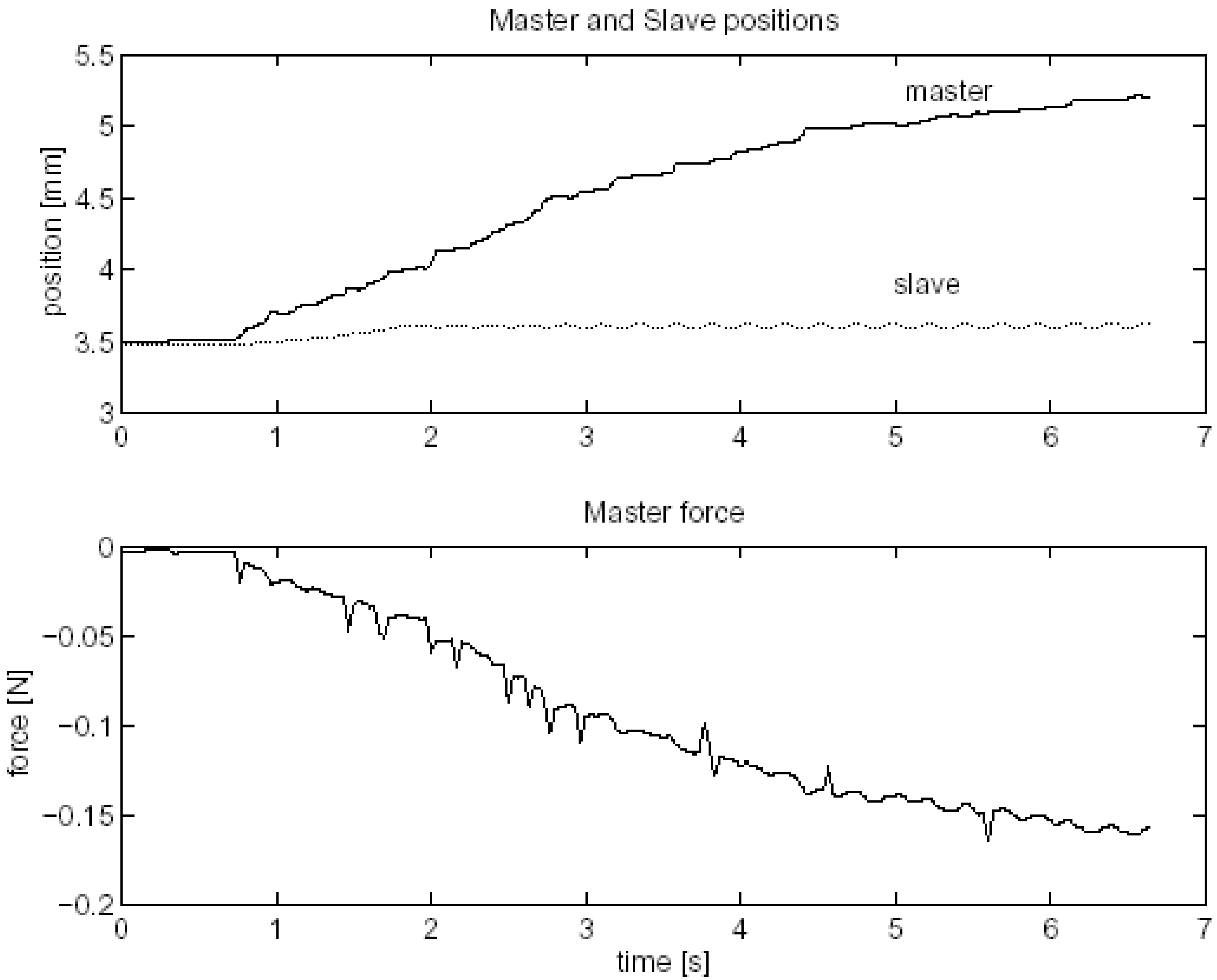


# Example



Master (solid) and Slave (dash) position
0.03
0.02
0.01
0
−0.01
−0.02
−0.03
[m]
0
1
2
3
4
5
6
7
8
9
10
Command (solid) and Feedback (dash) force
0.2
0.1
0
−0.1
−0.2
[N]
0
1
2
3
4
5
6
7
8
9
10
time [s]

# Results with local connection



# Results with long distance connection