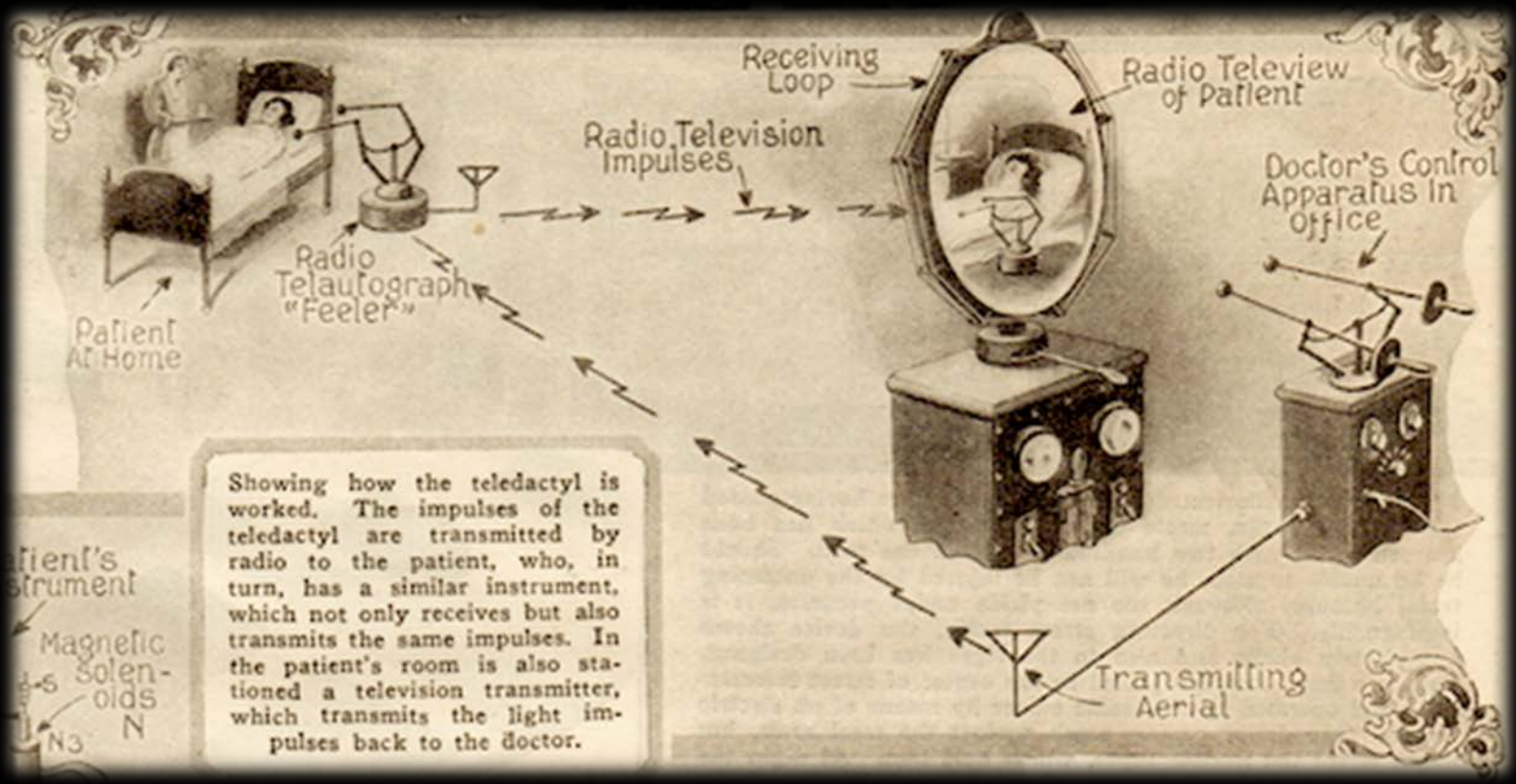
# Radio Teledactyl, 1925



# Haptic Applications pt II: Telemanipulation

## Evolution and Revolution

Delft Haptics Lab, Delft University of Technology, The Netherlands

**Jeroen Wildenbeest & Henri Boessenkool**

| | |
|---|---|
| **Oct 2011 – current** | **PhD Candidate, TUD** |
| **Nov 2010 – current** | **Consultant at Heemskerk Innovative Technology B.V.** |
| **Oct 2010** | **MSc Mechanical Engineering (track BCD), TUD** |

# Contents / Learning Goals

**After this lecture, you must be able to:**

1. **Reproduce:**
   - Explain the concepts of (tele)presence and transparency
   - Describe multiple control methods and their specific (dis)advantages

   **Apply:**
   - Explain how the different components of a teleoperation system affect device performance
   - Extrapolate on the examples of when haptic feedback can be important
2. **Think critically about:**
   - Findings and implications of several experiments regarding the significance of haptic feedback

# About opening doors…

## …with robotic systems

(1995) “The operation of the robot has to be improved, because currently the door opening task takes too much time”

**M. Saitoh et al. “*A mobile robot testbed with manipulator for security guard application*.”**

(2008) “Autonomous manipulation of doors remains a challenging problem after more than a decade of research”

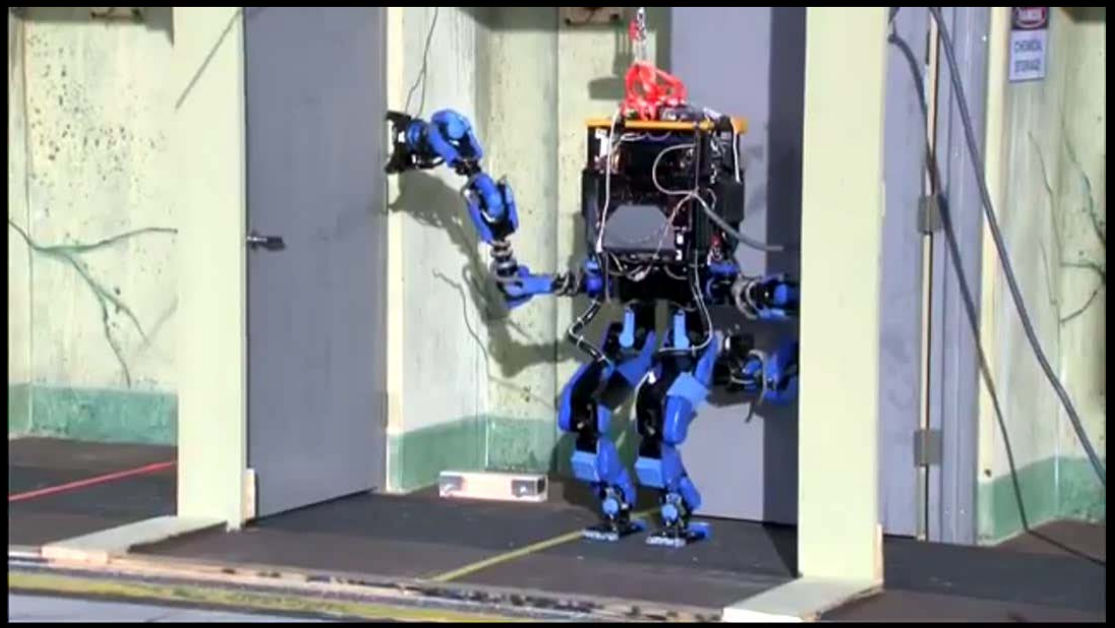
**Jain and Kemp “*Behaviour for Robust Door Opening and Doorway Traversal With a Force-sensing Mobile Manipulator.*”**

(2004) “Even trained operators are 5 times longer to open doors with a mobile robot than in direct contact”

**N. Nitzsche and G. Schmidt. “*A mobile haptic interface mastering a mobile teleoperator*.”**

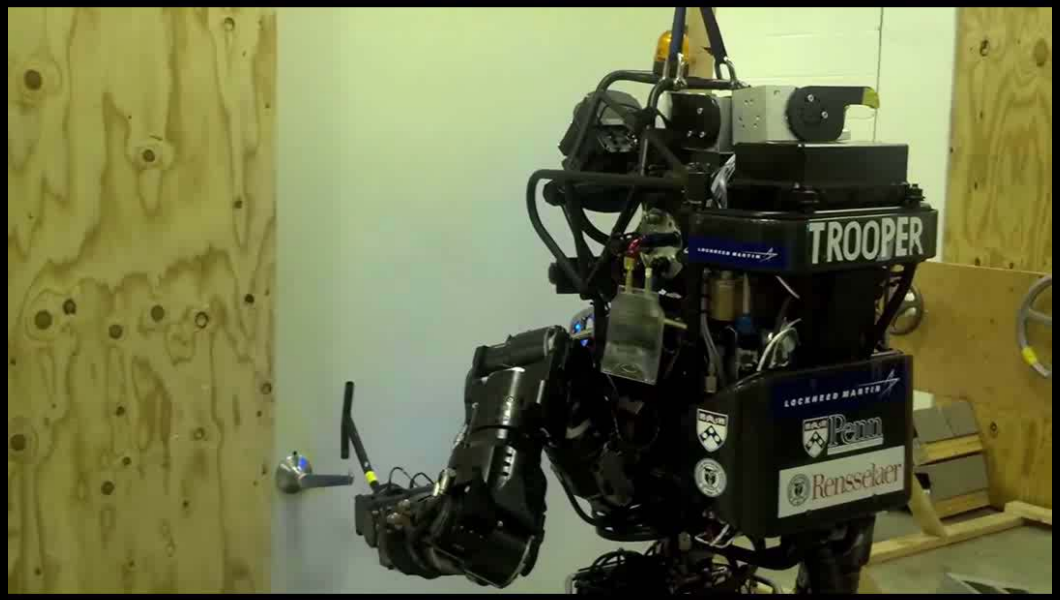
(2011) “Much of our training in Japan (Fukushima) was focused on using the PackBot to open doors”

**Indra Purkayastha Sr. VP at iRobot, Denison, D.C. “*Packbots explore stricken reactor.*” The Boston Globe. 2011, April 19**



5x (?)

# 2013 DARPA Robotics Challenge



# Why is it so hard - for a robot - to open a door?

# What makes it so easy for us?

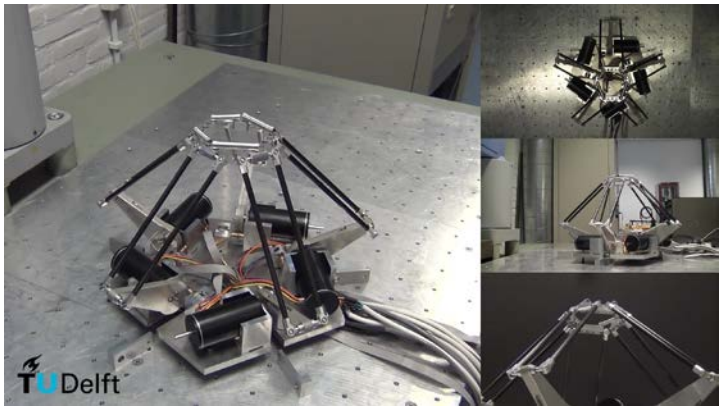
[1] [Lawrence, 1993]

# Problem

## We cannot design the ultimate telemanipulator

**Problem:** despite many decades of research, telemanipulation

- yields unnatural interaction
- causes frustration for the human
- takes too much time
- too many mistakes
- **Why?**

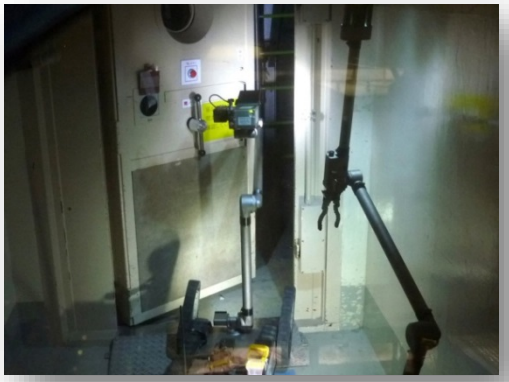



1. **Limitations of robotic system**
2. **Heavy focus on device, insufficient understanding of the human operator**

# Part 1:

## State-of-the-Science:
Developing, controlling and evaluating a telemanipulator

# Telemanipulation
## Human-in-the-loop control



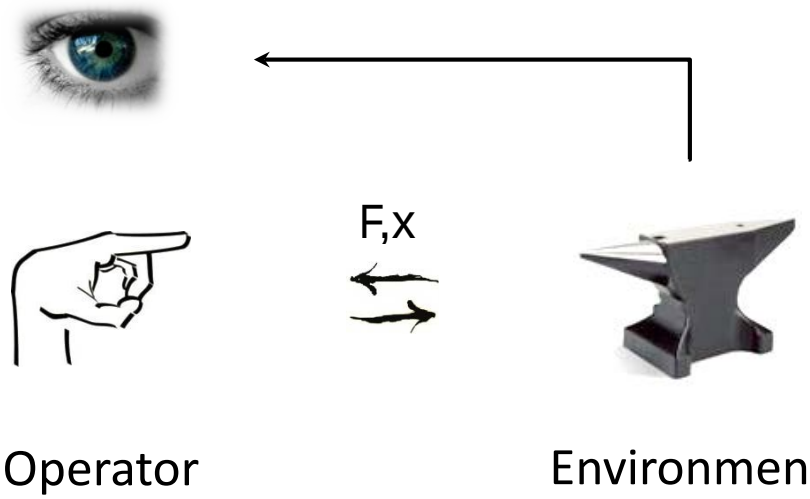
- You don't want humans in environments with:
  - In hostile environments (e.g. deep-sea, space, nuclear maintenance, IED)
  - With physical constraints (care & cure, micro-assembly)
- Some tasks require a human capabilities:
  - Manual skill
  - Cognitive capabilities (e.g. judgement, decision making)
  - Flexibility (open vs closed world)
  - Social interaction
- Biggest challenge: **how to design the tool?**

→ Better tools save time and money!

# Introduction

## From Manipulation…

- Two most effective modalities for manipulating objects[2]



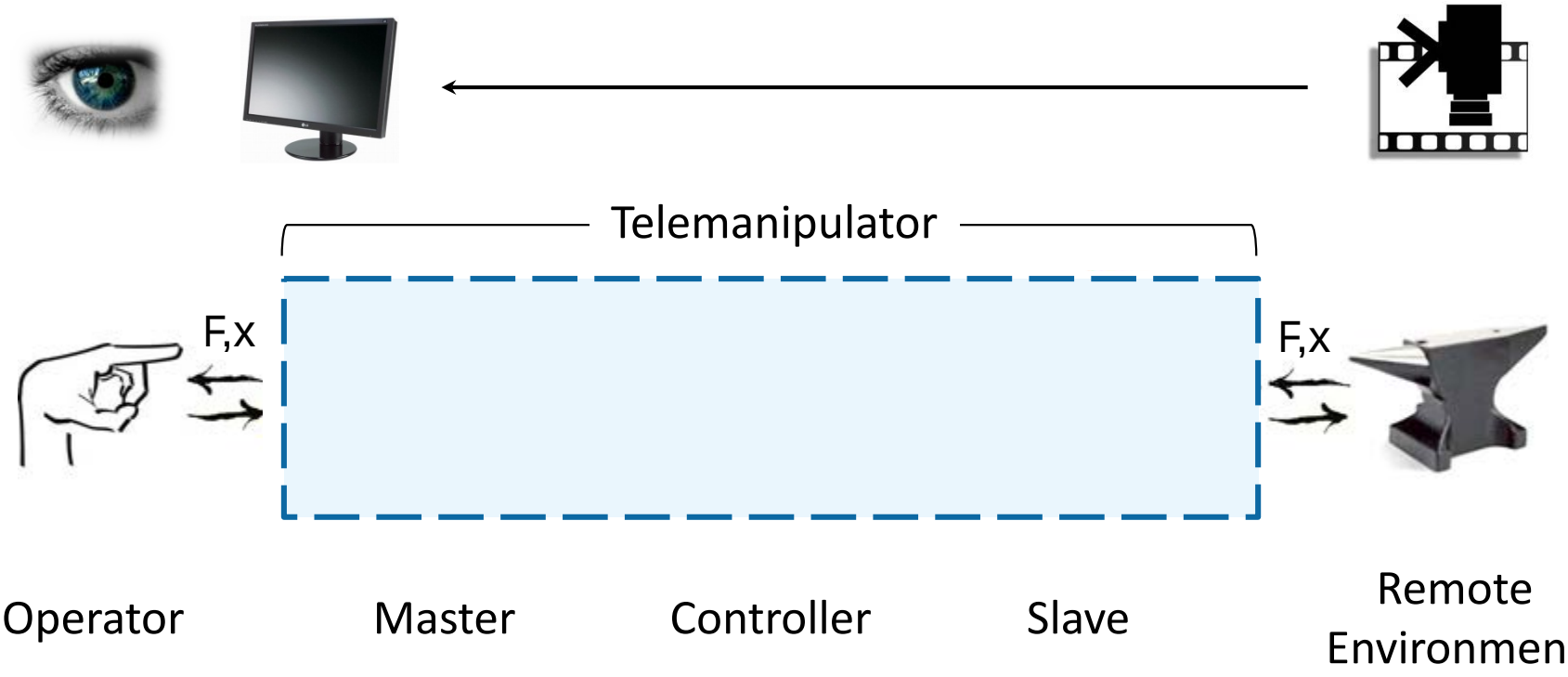

Haptic Feedback improves

- Task-completion-times
- Interaction forces
- Errors
- Workload

[2] H.S. Vitense, *"Multimodal Feedback: An Assessment of Performance and Mental Workload,"* Ergonomics, Vol. 46, 2003

# Introduction

## …To Telemanipulation



# Requirements

## An infinitely stiff and small rod


Goal:

- $Z_{out} = Z_{in}$ [7, 9]
- $x_{out} = x_{in}$ AND $F_{out} = F_{in}$ [8]
- $Z_{in}/Z_{out}$ [10]

(Traditional) Requirement:

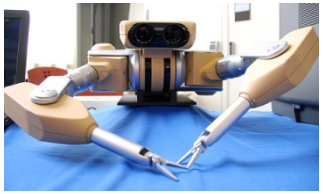
- Optimizing for “transparency”
  - Accurate rendering of task impedance [7, 9, 10]
  - perfect tracking of positions and positions[8]
  - Bilateral!
- While maintaining stability

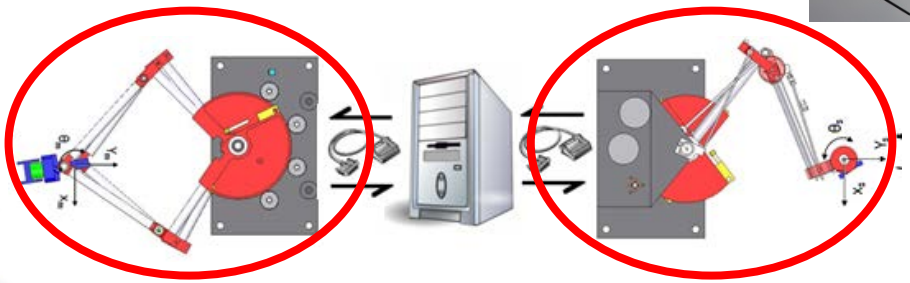
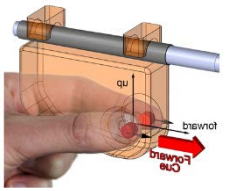


[7] Dudragne et al., 1989
[8] Raju et al., 1989
[9] Yokokohji and Yoshikawa, 1994
[10] Lawrence, 1993

# Requirements

## What affects transparency?



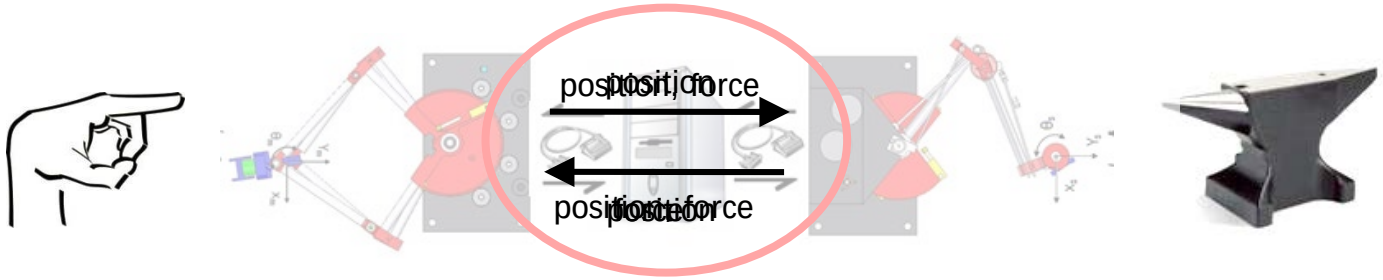
Master and Slave

- Construction: Mass, damping and stiffness
- Actuators: dynamic behavior
- Transmission: Friction, play, hysteresis
- Joints: Friction, play, hysteresis

[7] Dudragne et al., 1989
[8] Raju et al., 1989
[9] Yokokohji and Yoshikawa, 1994
[10] Lawrence, 1993

# Modeling

## What affects transparency?




Common Control Algorithms:

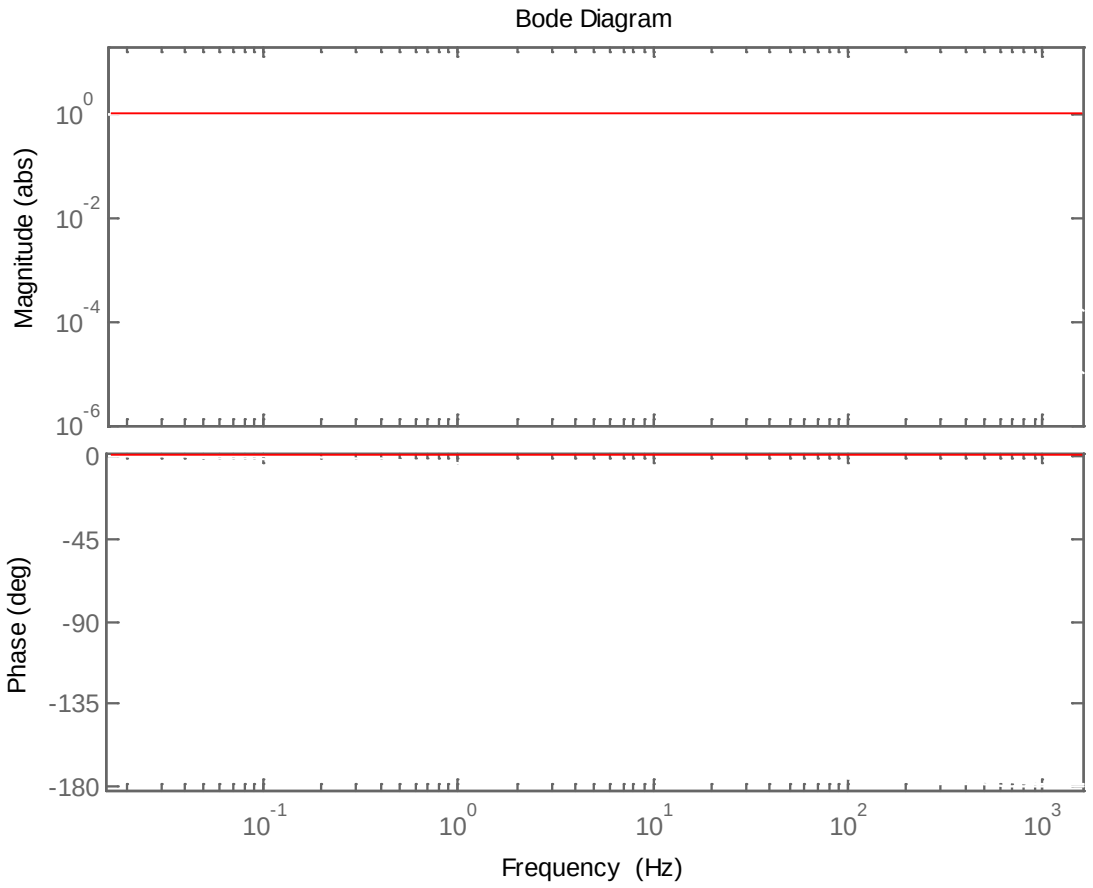
- Position – Position[3], correcting for position error between master and slave, stiffness limited by controller
- Position – Force[3], common industrial robot 'impedance' control, stability heavily affected by slave mass[5]
- 4-Channel Control[4], force sensor required, controlling all flow variables, yields superior performance[6]

[3] D.A. Lawrence, 1993
[4] K. Hashtrudi-Zaad et al., 1999
[5] Daniel and McAree., 1998
[6] I. Aliaga et al., 2004

# Ultimate goal: Perfect Transparency

## What would perfect transparency look like?

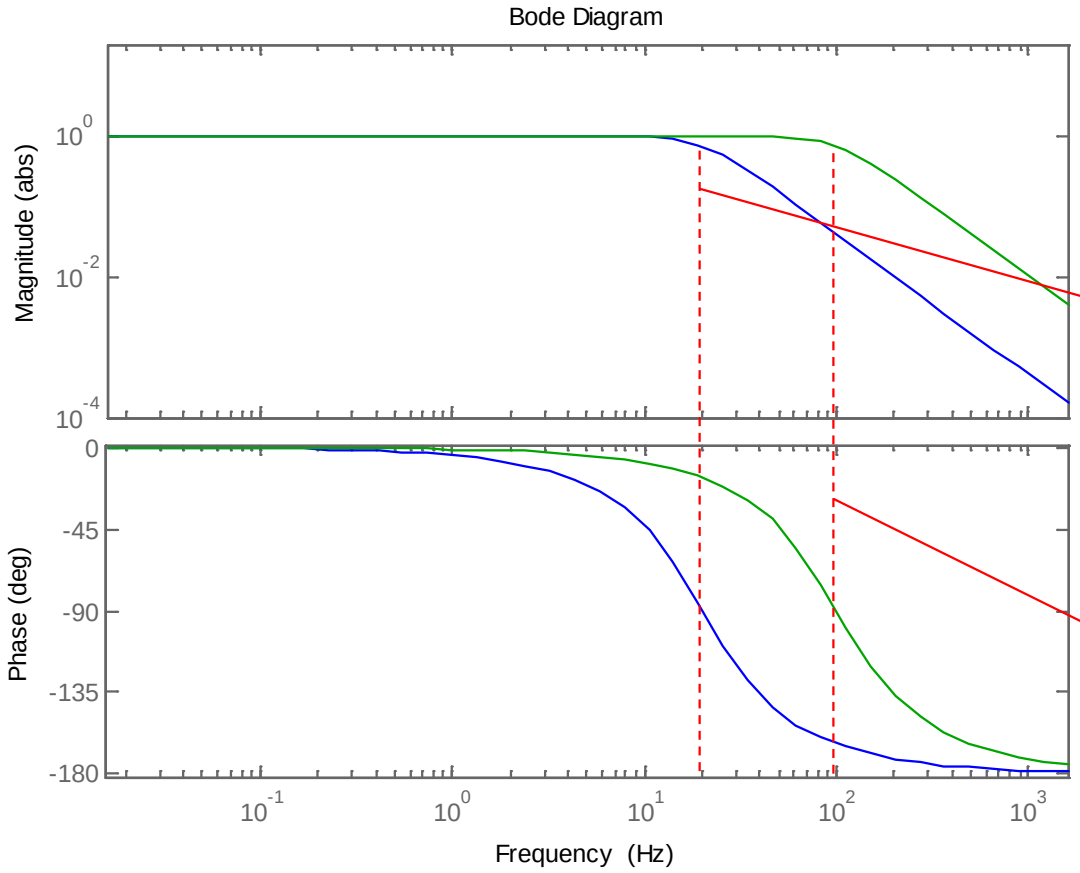
$$\left|\frac{Z_{out}}{Z_{in}}\right|$$



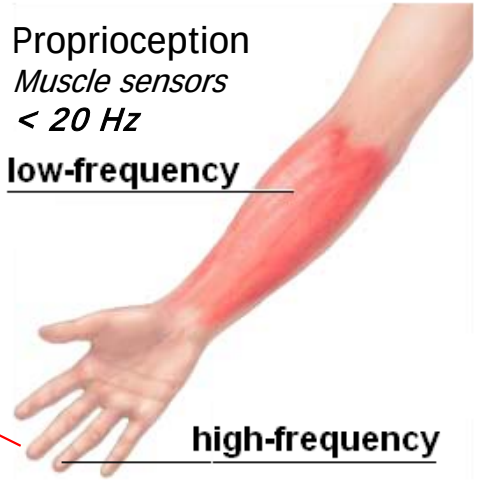
# Imperfect Transparency

## Device Bandwidth vs Human Sensory Information

$$\left|\frac{Z_{out}}{Z_{in}}\right|$$




Partition of Haptic Feedback, based on physiological properties[7]



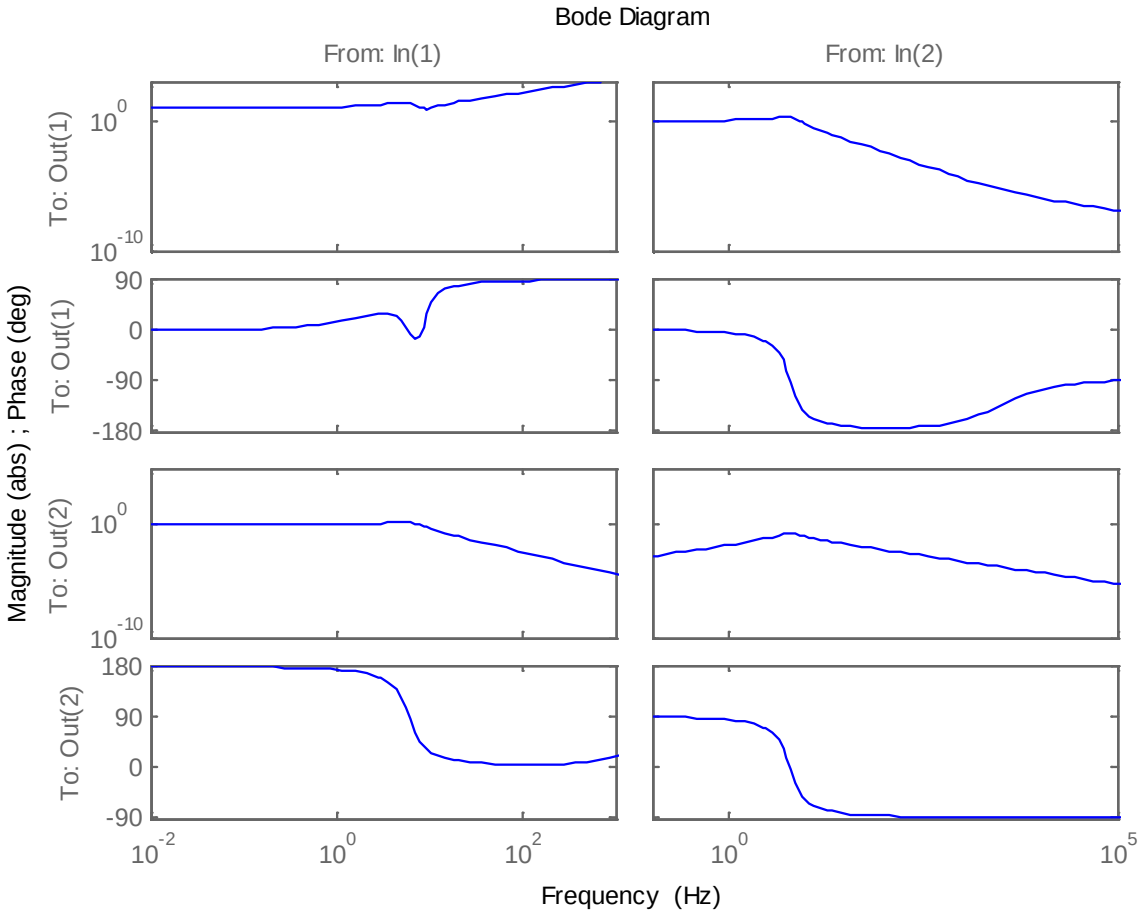
Proprioception
*Muscle sensors*
***< 20 Hz***
**low-frequency**

**high-frequency**
Mechanoreceptors
*Skin sensors*
***> 30 Hz***

[7] Daniel and McAree, *"Fundamental limits of performance for force reflecting teleoperation,"* Int. Journal of Robotics Research, 1998

# MIMO TFs

## Four in-output relations!



# State-of-the-Science

## Where are we now?

- Lots of knowledge on h/w and s/w (e.g. Hannaford, Hayward, Lawrence)
- After decades of research still problems with basic tasks → A strong need to improve!
- Perhaps improving transparency is not so effective after all?

# Part IIa:

# The significance of haptic feedback in human-in-the-loop telemanipulation

How important is haptic feedback?

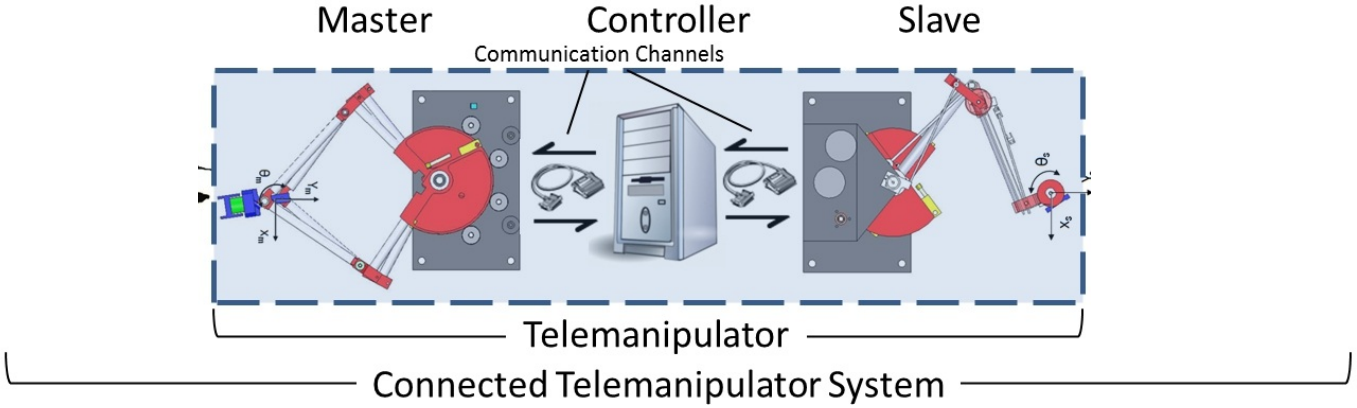
# How important is a good tool?

## How important is transparency?

**Transparency**

Accurate rendering of task impedance (F, x) from slave to master[2]

- but…transparency puts focus on improving the telemanipulator itself
- **How does improving transparency, contribute to improving the total system?**

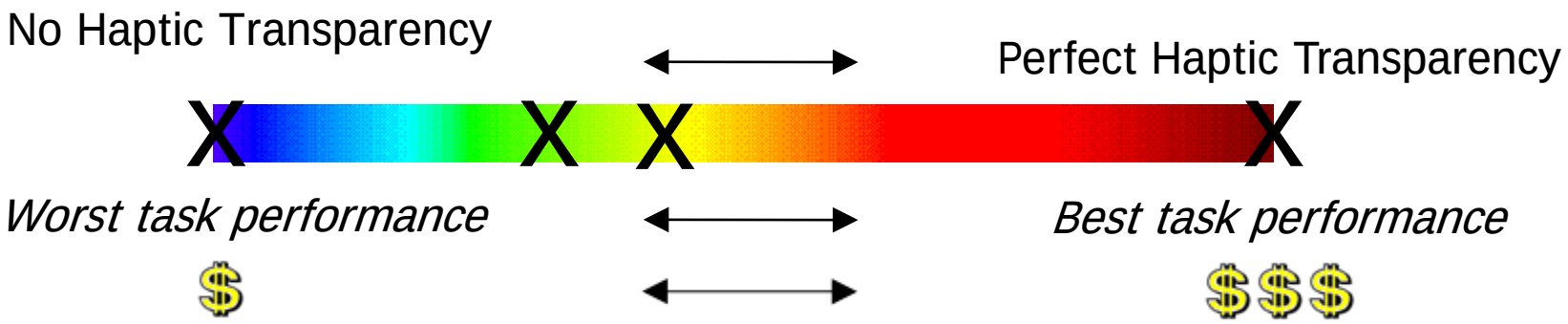



[2] D.A. Lawrence.,*"Stability and Transparency in Bilateral Teloperation,"* IEEE Transactions on Robotics and Automation, 1993

# Human Factors Experiment[8]

## Level of Transparency

- **Goal:** Assess task performance for different transparency levels displayed to the human operator
- 4 levels of feedback: $TC_{NF}$, $TC_{LF}$, $TC_{LFHF}$, DC)



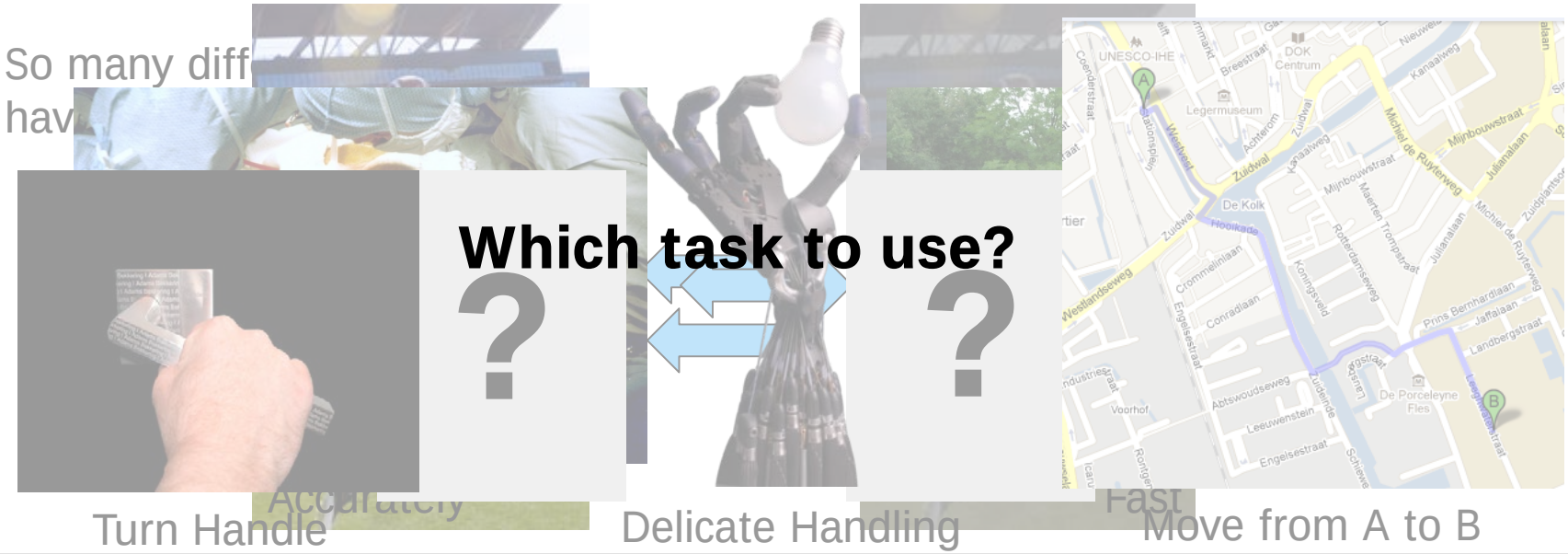

[8] J.G.W. Wildenbeest et al., *"Performance of Teleoperated Assembly Tasks Primarily Benefits From Low-Frequency Haptic Feedback,"* IEEE Transactions on Haptics, 2012, in press

# Introduction

## Factors of influence…

Other factors that influence task performance:

- the quality of visual feedback
- task instruction
- type of task



# Introduction

## Fundamental Tasks!

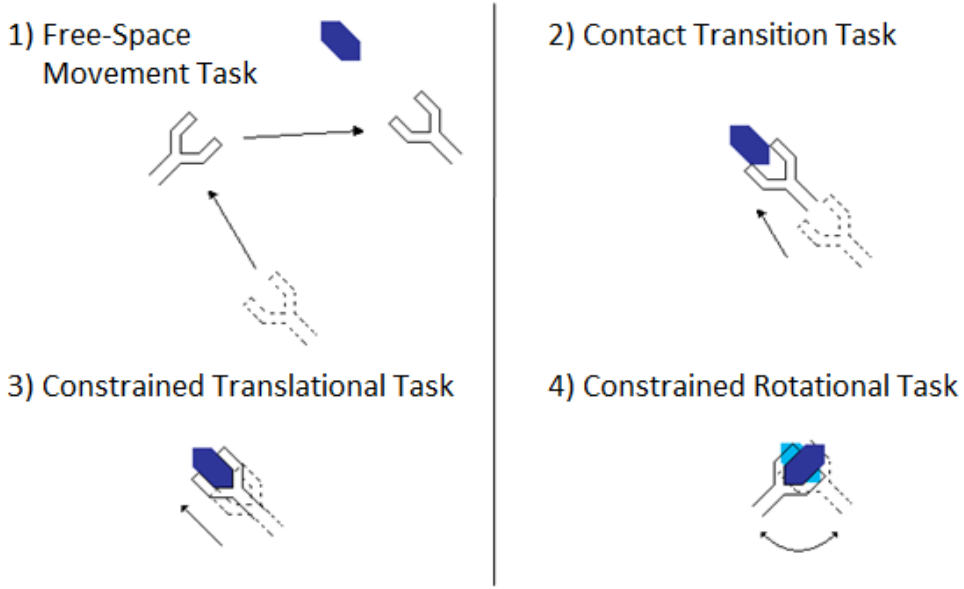
**My reference task:**

A task that contains common aspects of tasks

Four fundamental tasks:

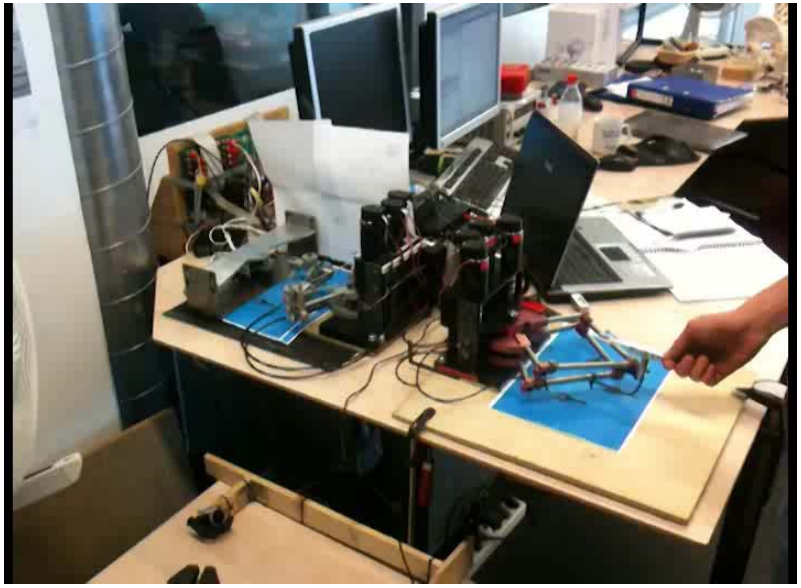
1) Free-Space Movement
2) Contact Transition
3) Constrained Translational
4) Constrained Rotational

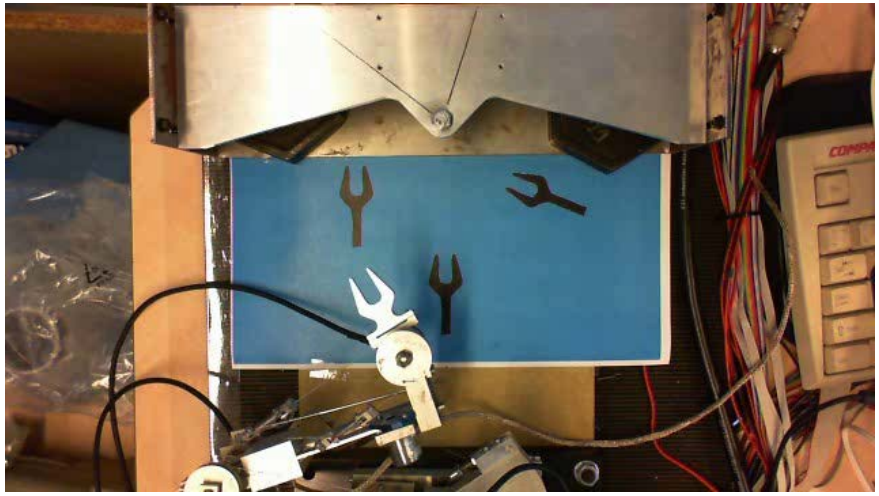
**Identified in a single bolt-and-spanner task!**



# Method

## Experimental Setup - the 'Munin' teleoperator[3]





[3] G.A.V. Christiansson, *"A novel 3-dof Planar Haptic Teleoperation System,"* Proc. of IEEE WorldHaptics Conference, 2007

# Results

## Whole task

Clear pattern!

more haptic feedback

→better performance

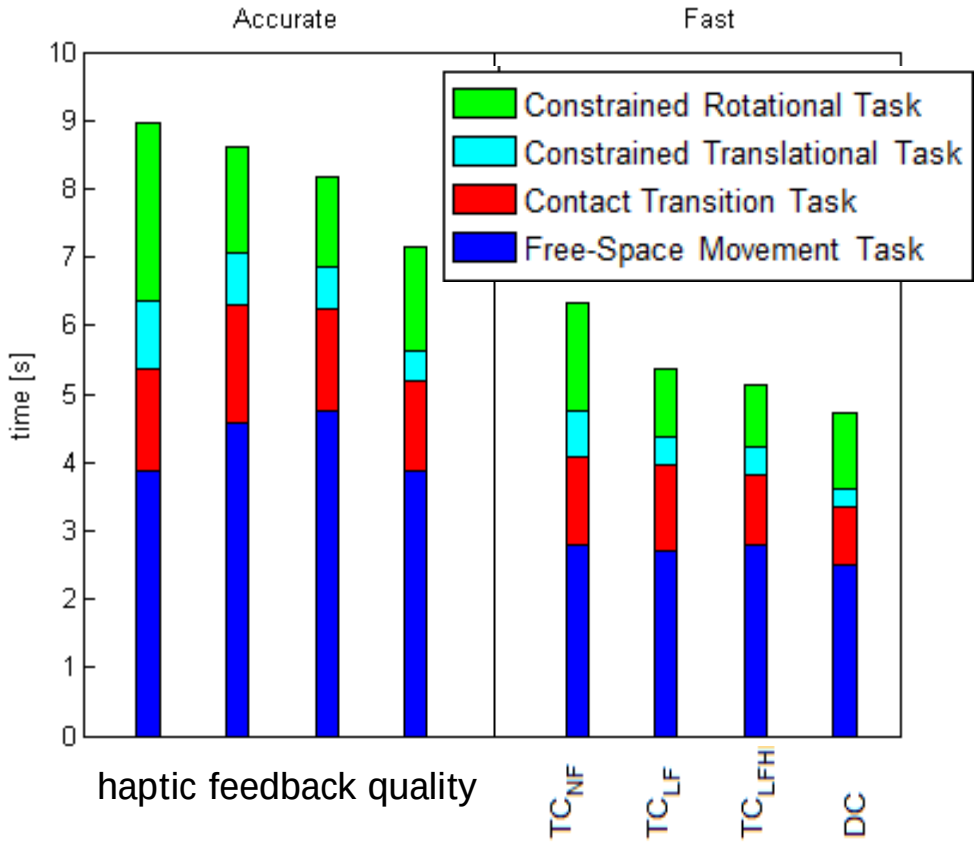
**or…?**

Marginal Effects for:

1) Contact Transition (●)
2) Constrained Translation (●)

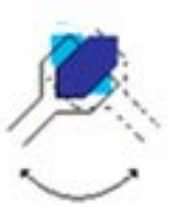
Remarkable effects for:

1) Free-Space Movement (●)
2) Constrained Rotational (●)



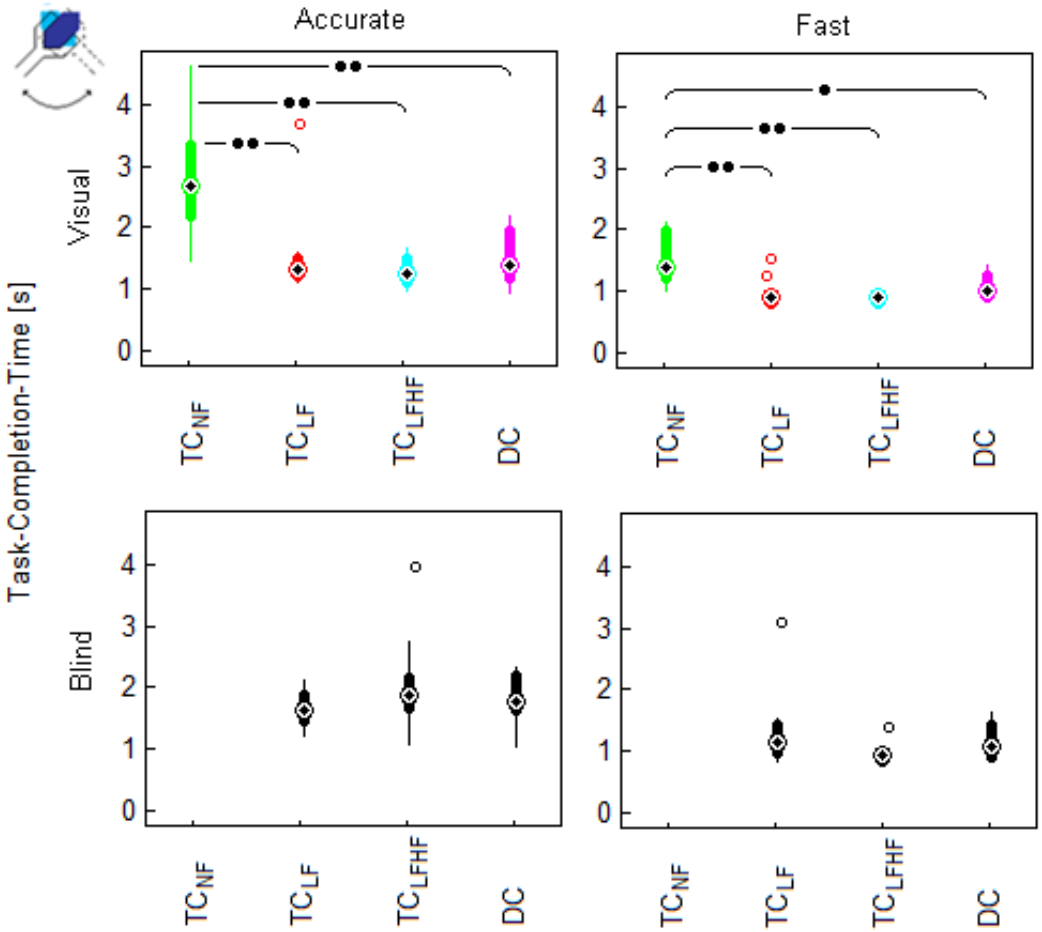
# Remarkable Results

## Constrained Rotational Task



Low-frequency transparency improves task performance and control effort ($p \leq 0.01$)

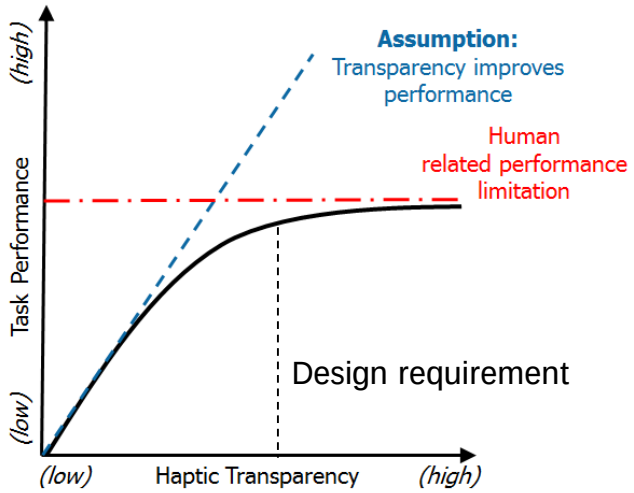
No difference between limited and full transparency!

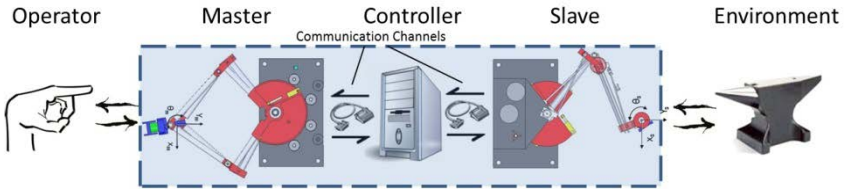


# Conclusions Part IIa

## The effect of transparency on task performance

- Improving transparency has only **limited effect on improving task performance** (for this particular experiment)
- Perhaps, we should **shift focus to techniques that directly support the operator** in performing his tasks, techniques that address task performance



# Limitations Part IIa

## For which tasks do these conclusions hold?

- Hard-hard environment
- Compliant slave
- Repetitive tasks
- ..

Repetitive nature

[8] J.G.W. Wildenbeest et al., *"Performance of Teleoperated Assembly Tasks Primarily Benefits From Low-Frequency Haptic Feedback,"* IEEE Transactions on Haptics, 2013

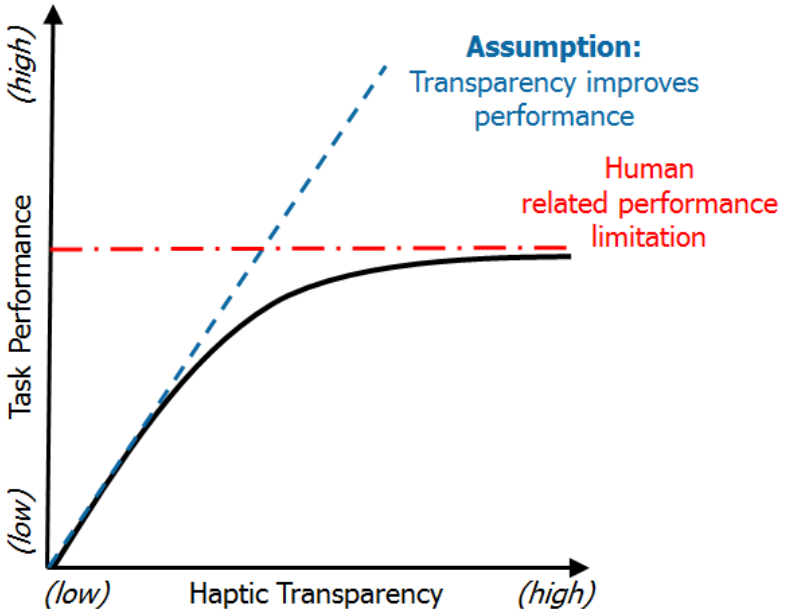
# Background

## Teleoperation

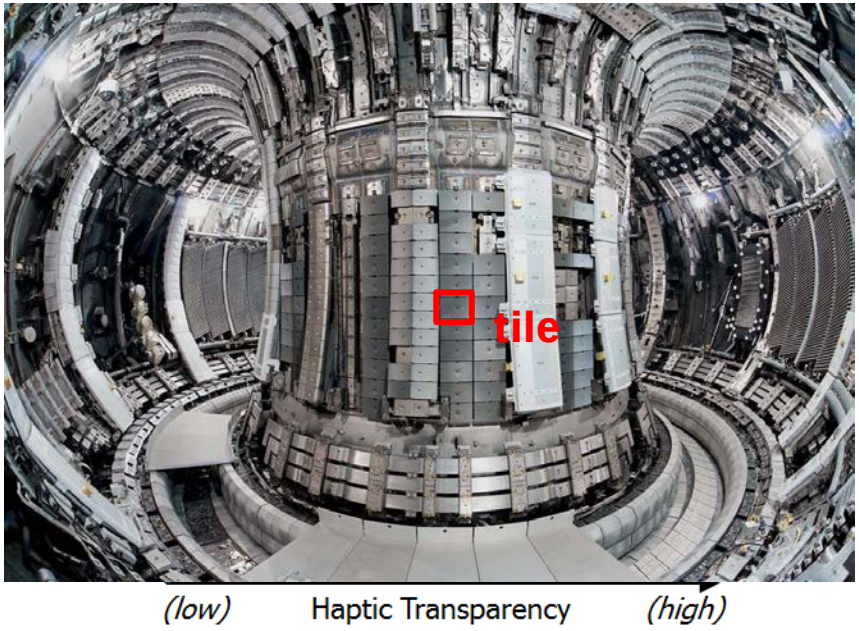
[1] [Lawrence, 1993]
[2] [Hannaford, 1989]
[3] [Aliaga et al., 2004]
[4] [Lawrence, 1993]
[6] [Daniel and McAree, 1998]
[7] [Draper et al., 1987]
[8] [Hannaford et al., 1991]
[Christiansson et al., 2007]
[11] [Widenbeest et al., 2012]

Repetitive nature

**Literature:** repetitive tasks




**In practice:** tasks are similar, but unique



# Part IIb:

# The significance of haptic feedback in human-in-the-loop telemanipulation

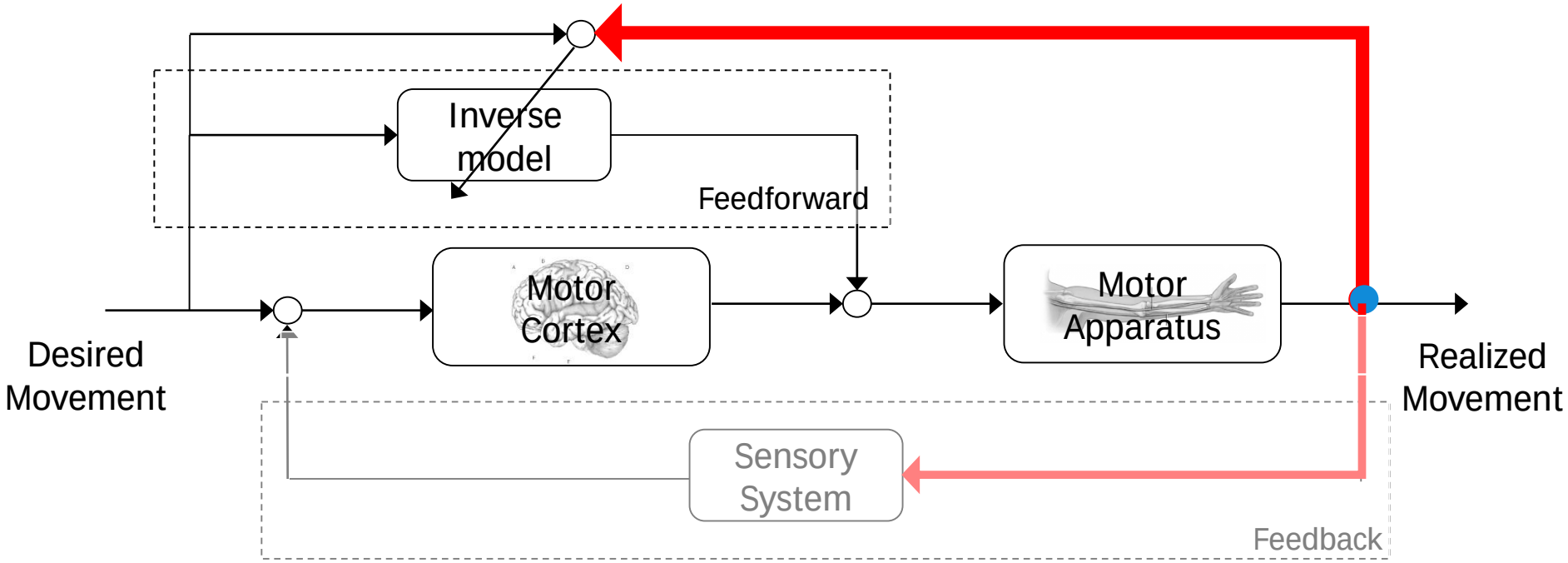
How important is haptic feedback for learning task dynamics?

# Background Theory

## Motor control

= Full transparency (direct control)

= Reduced transparency (teleoperation)




Adapted from [Kawato, 1987] [Ito, 2001] [Passot & Arleo, 2010]

## Hypothesis

**A high level of haptic transparency improves**
**a) the rate, and**
**b) generalizability**
**of learning task dynamics**

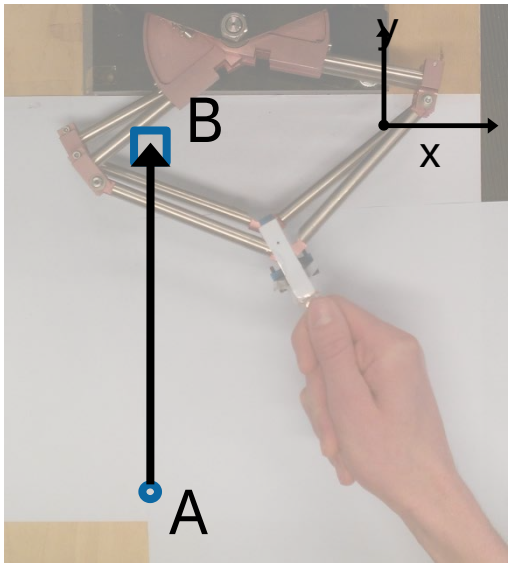
# Introduction
## Motor learning experiments

Perturbing Force Field:

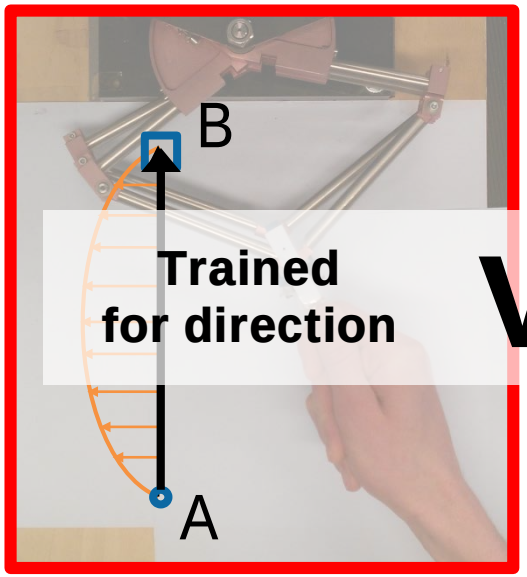
$F = B\dot{x}$ :

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} 0 & -7 \\ 7 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}_x \\ \dot{x}_y \end{bmatrix}$$

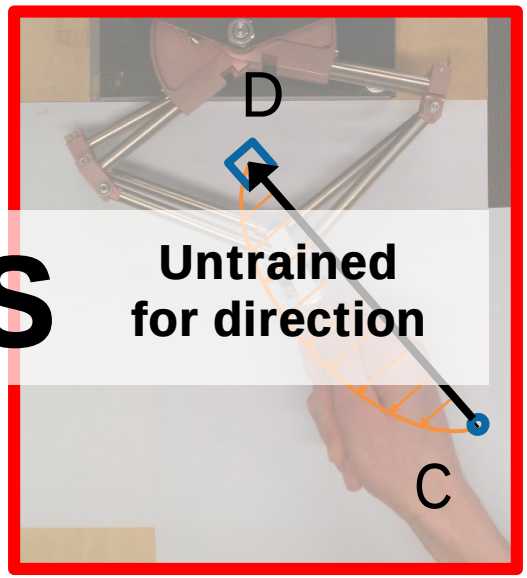
- Reach adaptation task (paradigm adapted from [Haswell et al, 2009])
- 3 stages, quick (feedforward) movements




**Stage 1:** Familiarization

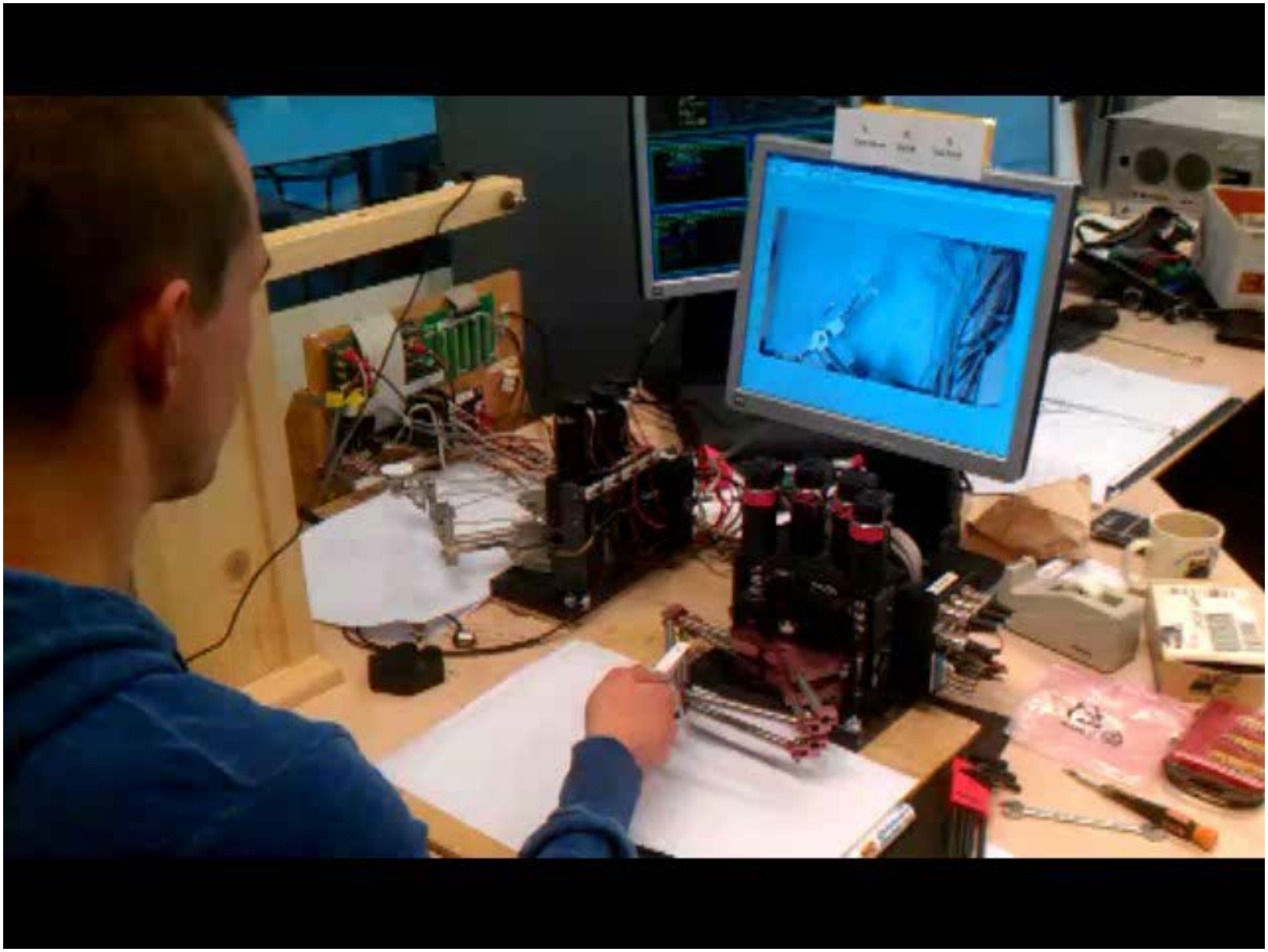



VS




**Stage 2:** Learning

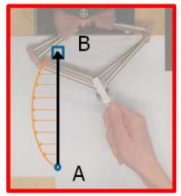
**Stage 3:** Generalization



= Full transparency (direct controlled)

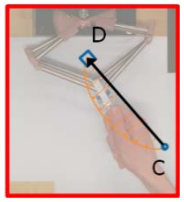
= Reduced transparency (teleoperated)

# Results - Trajectories



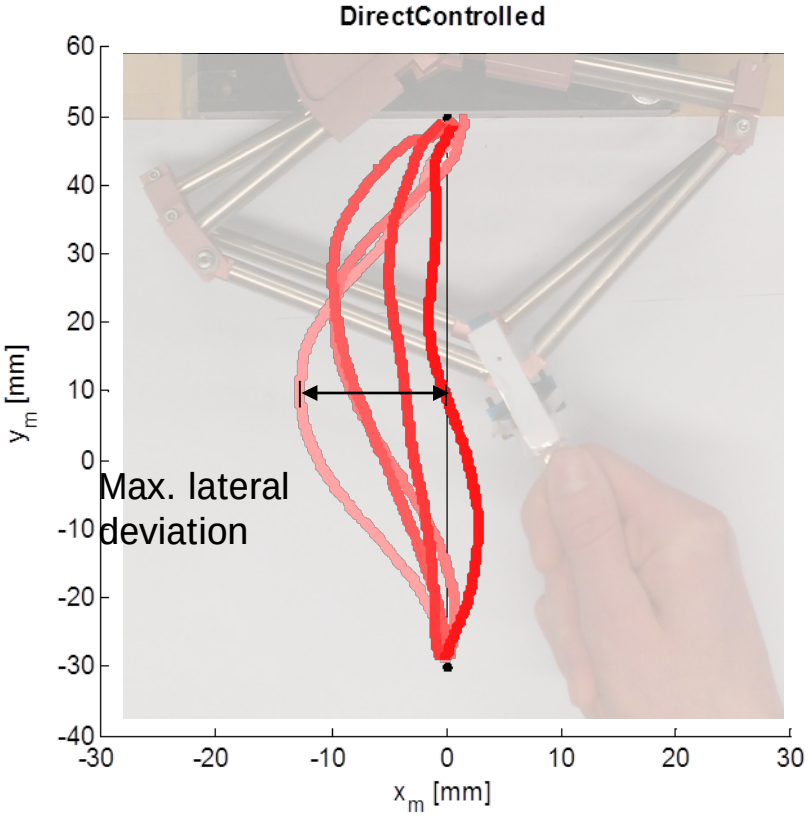

**Stage 2:** Learning

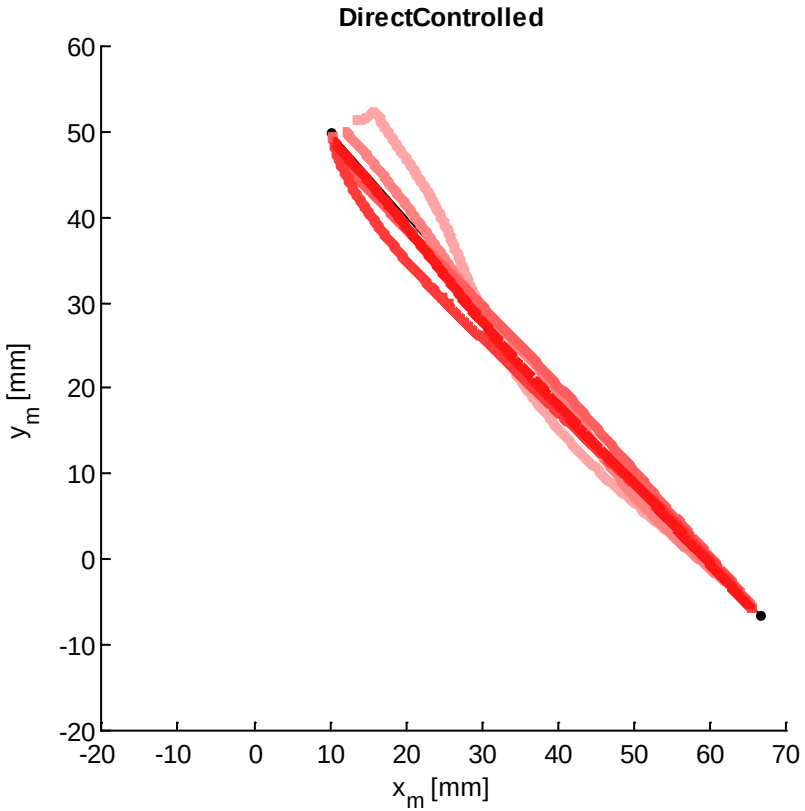
**Trained for direction**




**Stage 3:** Generalization

**Untrained for direction**

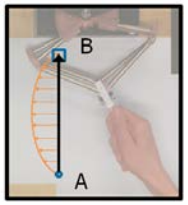


= Full transparency (direct controlled)

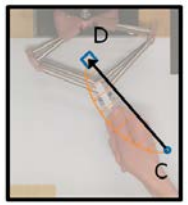
= Reduced transparency (teleoperated)

# Results – Max. dev.



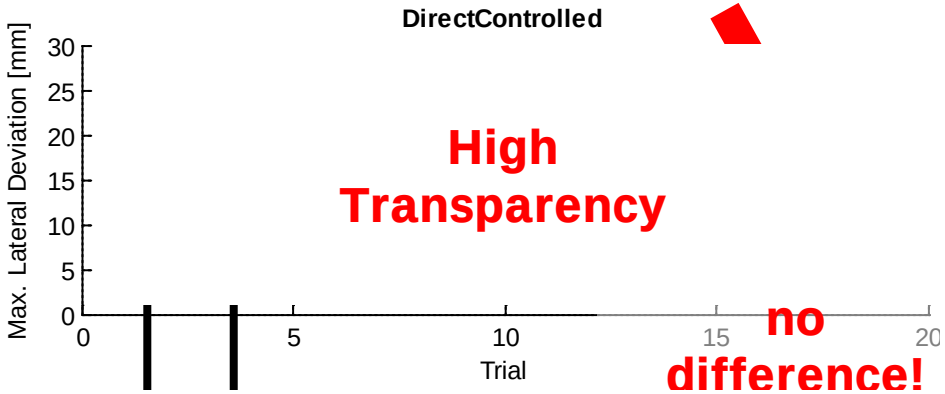

**Stage 2:** Learning

**Trained for direction**




**Stage 3:** Generalization

**Untrained for direction**




**High Transparency**

**no difference!**

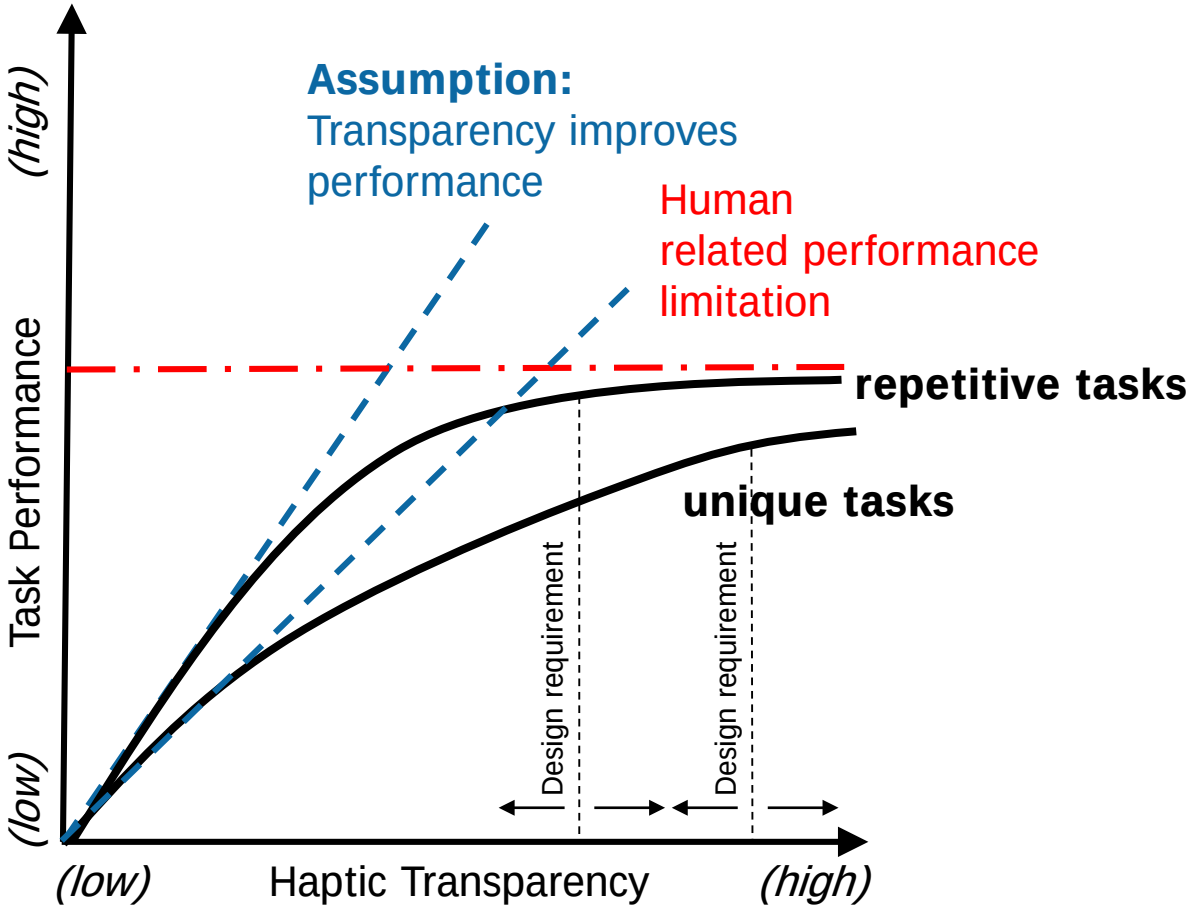
**Reduced Transparency**

# Conclusion

## Transparency affects motor learning!

- A high haptic feedback quality allows for more rapid adaptation and more accurate behaviour in situations that have not yet been encountered.
- Transparency may not only affect low-level coordination, i.e. at muscular level, but it also affects neuromuscular coordination and planning
- The significance of haptic feedback is context dependent:
  - Task performance (online task execution) VS motor skill (offline training)

# Implications



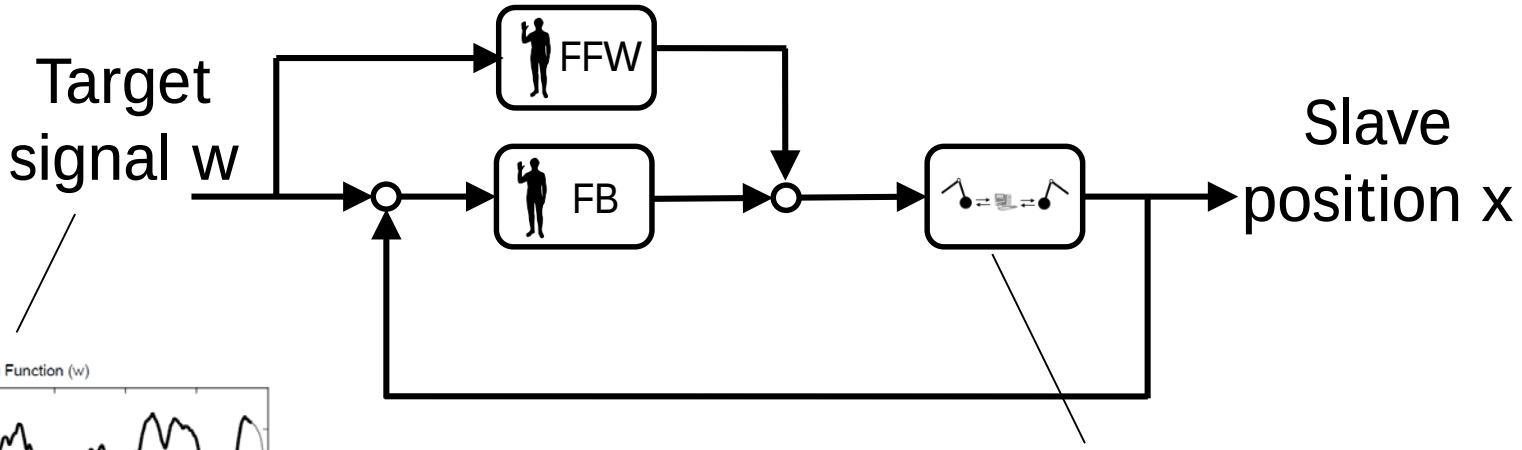
# Part IIc:

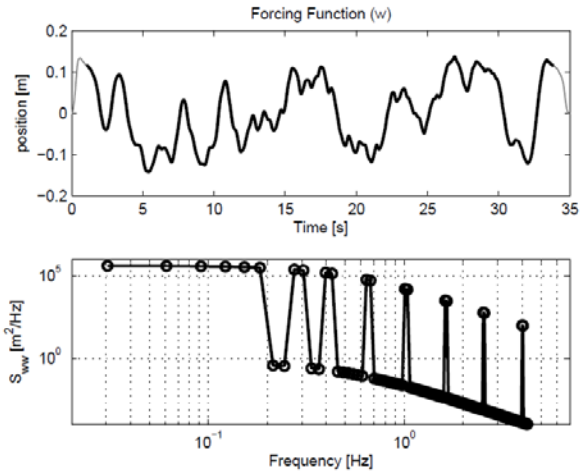
# The significance of haptic feedback in human-in-the-loop telemanipulation

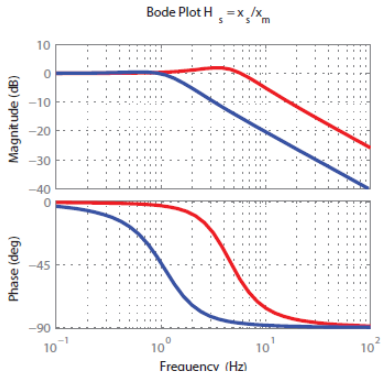
How important is haptic feedback for systems with different dynamics?

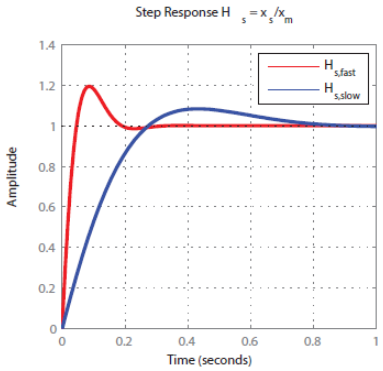
# Haptic Feedback…

## …for fast and slow dynamic systems



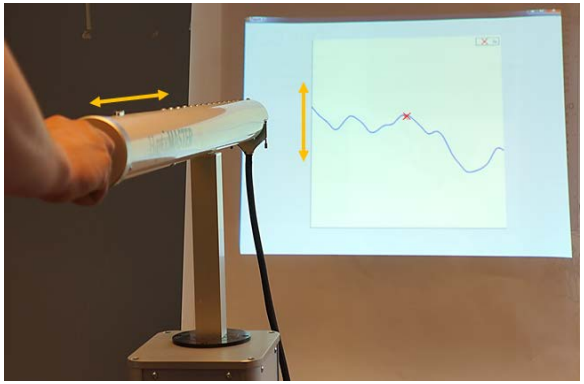



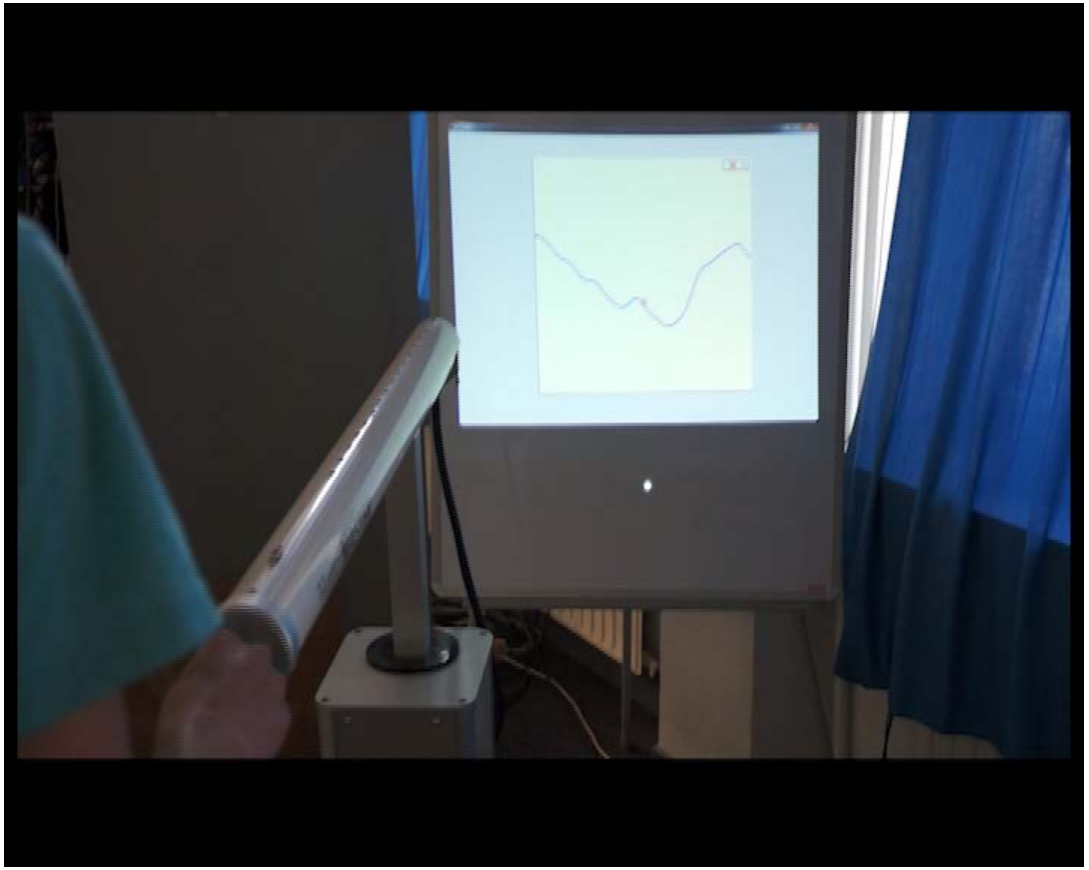



# Haptic Feedback…

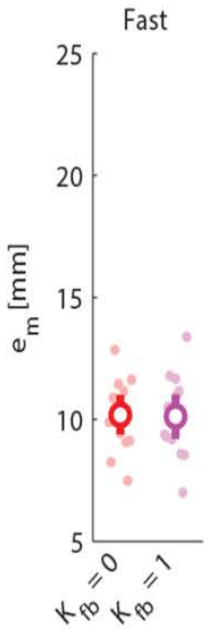
## …for fast and slow dynamic systems





# Haptic Feedback…

## …for fast and slow dynamic systems



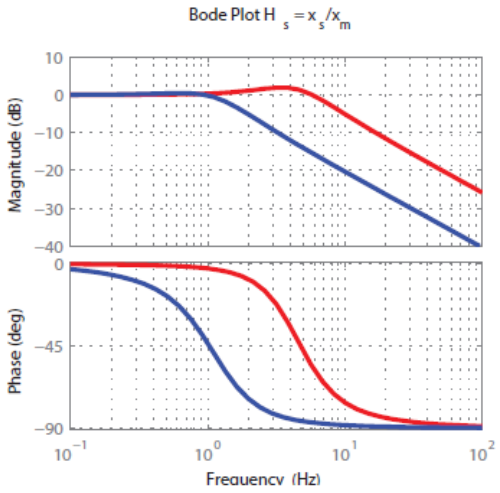
# Conclusion

## Transparency affects motor learning!

- Providing feedback of mass and damping of the controlled system allows operators to anticipate upon the system's limitations,
  - but only if the system is slower than the human operator (reversal rate, tracking error frequencies >1.5 Hz)
  - independent of amplitude

Reason?

- Hypothesis: Operator is able to generate lag to compensate for the system's lead



# Take Home Measages

**Part I:** State-of-the-Science

- Traditional design goal: Optimizing for **transparency** while maintaining **stability**
- Developing telemanipulators requires a **multi-discliplinary** approach!

**Part II:** Experiments

- Significance of haptic feedback is task and system dependent
- Haptic feedback improves task performance, but only till a certain extent
- For radical system improvements, perhaps we should **shift focus away from haptic feedback**

# How does this continue?