Adaptive Passivity Control for Haptic Transparency Enhancement of Multilateral Robotic Telerehabilitation in Virtual Reality Environments

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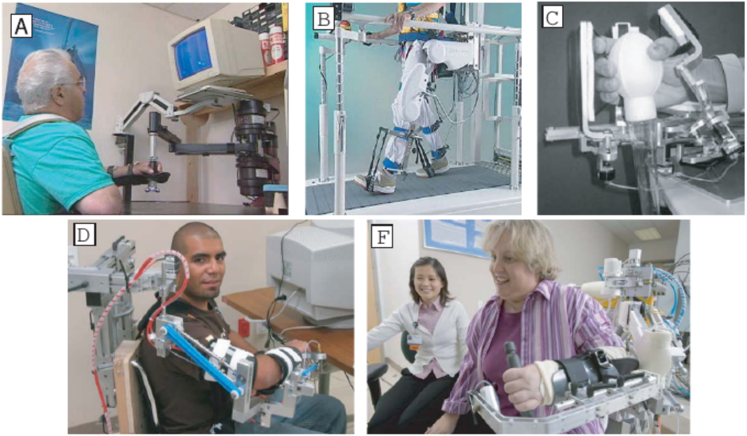
Sections

General Context

- Research in Robotic Rehabilitation (Krebs et al., 2008; Marchal-Crespo and Reinkensmeyer, 2009; Cao et al., 2014)

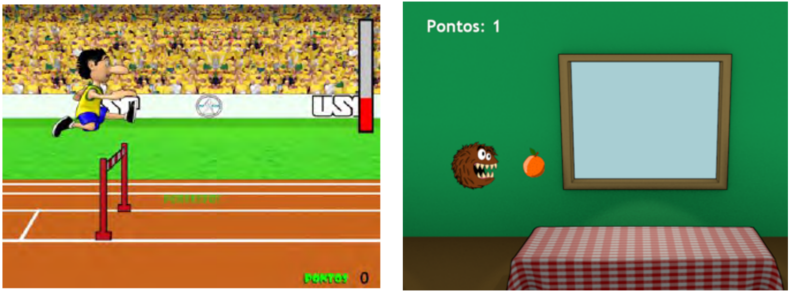


(Marchal-Crespo and Reinkensmeyer, 2009)

Robotic Rehabilitation

- Interface between therapists and patients
- Immediate advantages:
  - Facilitating therapist's work
  - Greater number of exercise repetitions
  - More precise assistance and adjustments
  - Objective performance analysis
- Enablement of new features:
  - Virtual reality: Serious Games (Andrade et al, 2013; Gonçalves et al., 2014; Pasqual, Caurin and Siqueira, 2016)
  - Long distance communication: Telerehabilitation (Carignan and Krebs, 2006; Atashzar, Polushin and Patel, 2012; Lanini et al., 2015)
  - Combination of both (Novak, Nagle and Riener, 2014)

Virtual Reality

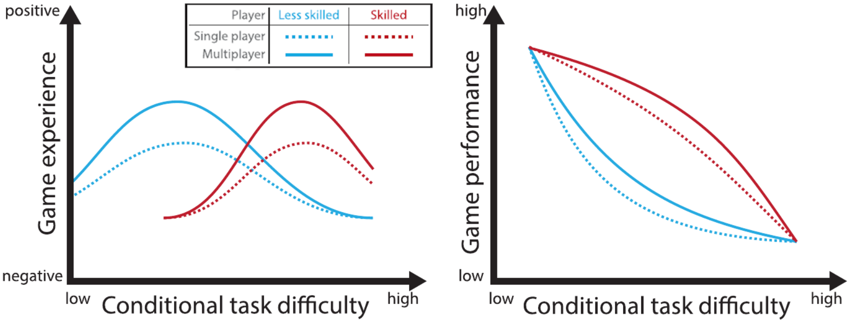


Serious Games (Gonçalves et al., 2014)

- Presenting goals in an intuitive way
- Simultaneous audiovisual and mechanical feedback
- Immersion: lighter cognitive load and pain/fatigue sensation
- Entertainment and motivation (for better recovery)

Serious Games

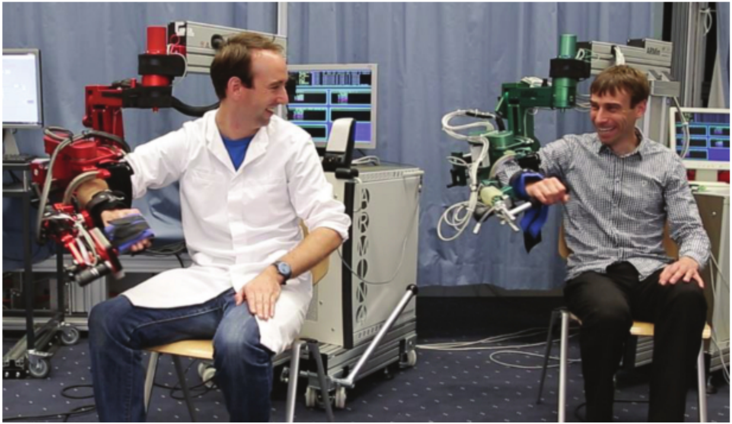
- Multiplayer: co-activity, competition, cooperation or collaboration (Jarrassé, Charalambous and Burdet, 2012)



Modified from Baur et al. (2018)

Robotic Telerehabilitation

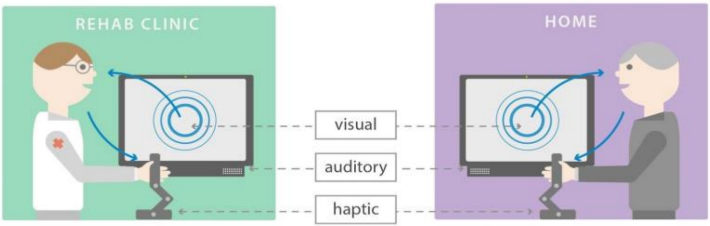
- Remote interaction between users



(Lanini et al., 2015)

Robotic Telerehabilitation

- Audiovisual and moto/haptic interaction



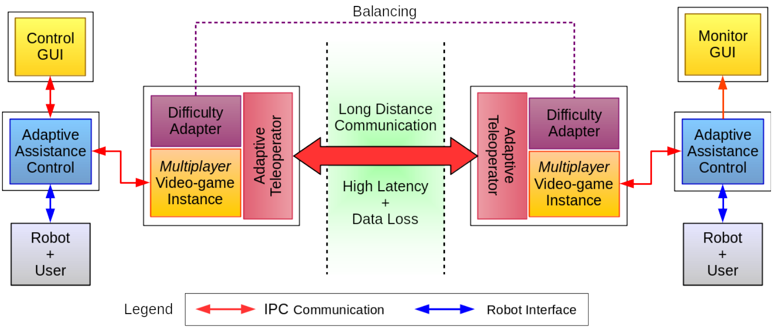
Modified from Minge et al. (2017)

Challenges Considered

- For local assitance (adaptation to patients):
  - Mostly static properties (e.g. anatomy)
  - Dynamic characteristics (e.g. evolution, fatigue)
- For telerehabilitation (stability vs performance):
  - Long distances (communication delays)
  - Low network quality (data loss)
- For socialization (balancing):
  - Collaboration/cooperation: distributed workload
  - Competition/co-activity: difficulty equilibrium

Motivation

- Base the 3 levels of adjustment on the same set of variables?
  - Integration: combining advantages of different systems
  - Simplification: lesser need for additional components



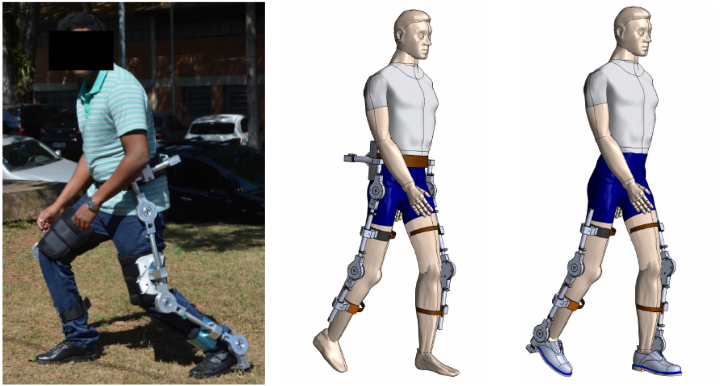
Objectives

- Mechanical properties as common parameters
  - Online automatic identification
  - Effort and dynamic behaviour estimations
- Focus on the teleoperation aspect
  - Network lag and data loss compensation
  - Faithful force reflection (transparency)
- Generalized platform
  - Interfaces for interchangeable parts
  - Multiple architectures
- Relevant data collection
- Documentation for usage and expansion

Sections

Rehabilitation Robotics

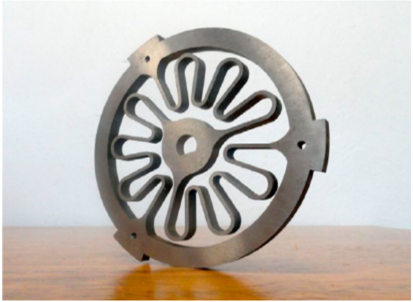
- Less rigid mechanisms + compliant control



(Dos Santos et al., 2017)

Rehabilitation Robotics

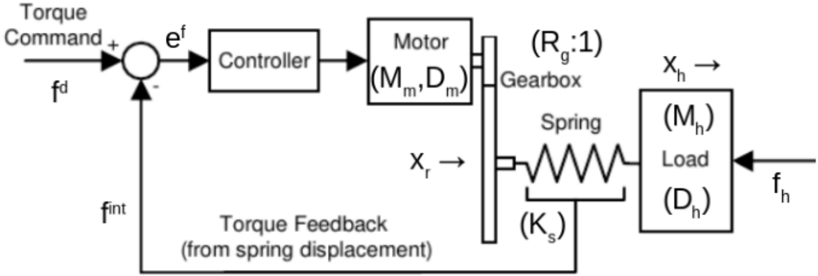
- Less rigid mechanisms + compliant control
- Series Elastic Actuators (SEAs)

(Dos Santos, Caurin and Siqueira 2017)

Rehabilitation Robotics

- Less rigid mechanisms + compliant control
- Series Elastic Actuators (SEAs)



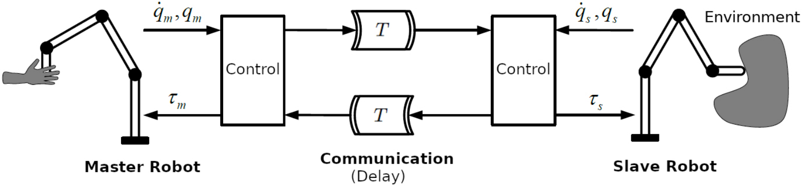
Modified from Wyeth (2006)

Rehabilitation Robotics

- Adaptive control (AAN):
  - Slacking Hypothesis
  - Impedance control (Hogan, 1985)
    - Simulation of stiffness, damping and inertia
    - Explicit definition of desired virtual values
    - Optimal/robust alternative: adjustable compromise
  - Interation with user/patient
    - External (user) force as disturbance
    - Effort estimation (e.g. EMG, DI)
    - Mechanical model: parameter estimation (grey-box)

Robotic Telerehabilitation

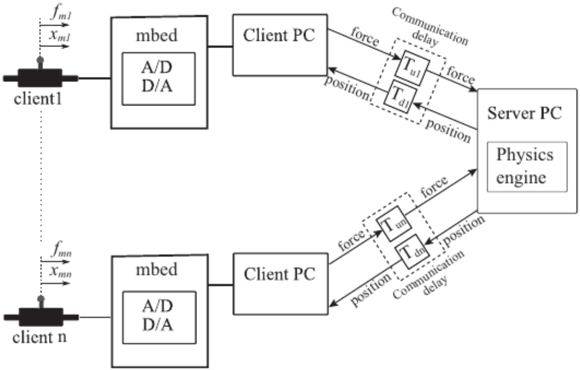
- Applies principles from robotic teleoperation
- Classification (Carignan and Krebs, 2006)
    - Unilateral: only user movement/position is mirrored
    - Bilateral: remote force feedback closes control loop



Niemeyer and Slotline (2004)

Robotic Telerehabilitation

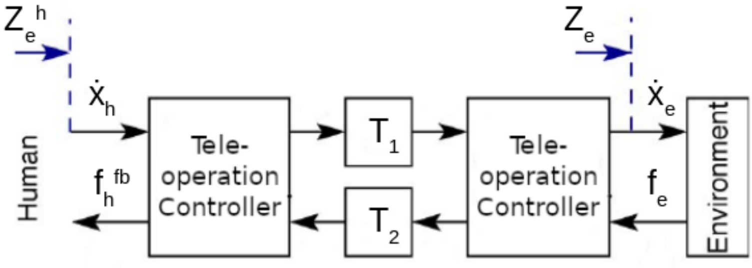
- Multilateral layout: bilateral case extension
- Client-side synchronization and prediction



(Kawase, Miyoshi and Terashime, 2016)

Bilateral/Multilateral Teleoperation

- Optimization problem
  - Stability: passivity ("weak"/local and "strong"/global)
  - Force reflection (transparency): learning/generalization



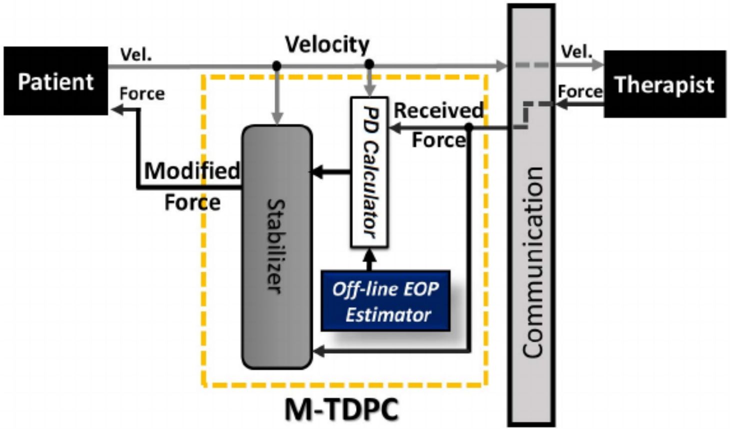
Modified from Hirche and Buss (2012)

Solutions for Bilateral Teleoperation

- Wave variables (Niemeyer and Slotline, 2004)
  - Virtual energy transmissions (measurable local passivity)
  - Guaranteed effectiveness for constant delay and passive environment
  - Wave reflections
    - Impedance modulation/matching (Rodríguez-Seda, 2015): complex switching
    - Wave filters: avoid need for extra controllers, energy loss, tracking error
- Small-gain criterion (H_∞ norm)
  - Ensure unitary gain limit for closed loop
  - Feedback force saturation (Atashzar, Polushin and Patel, 2012; Lanini et al., 2015)
  - Signal filters for robust control (Miyoshi, Terasima and Buss, 2006; Hirche and Buss, 2012)

Solutions for Bilateral Teleoperation

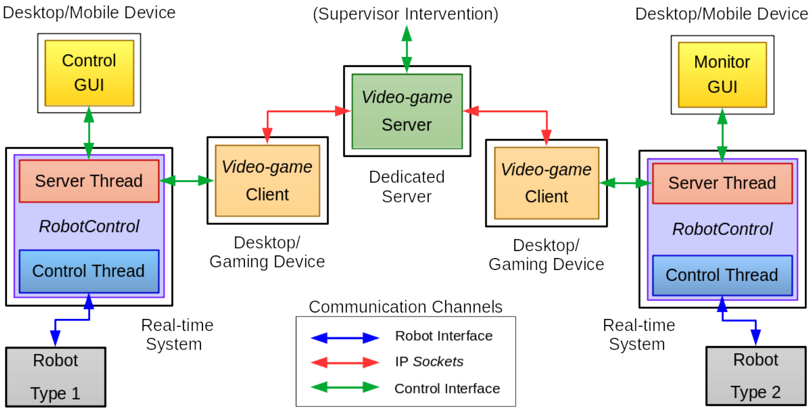
- Energy filters: global passivity control in the time domain (TDPC)



(Atashzar et al., 2017)

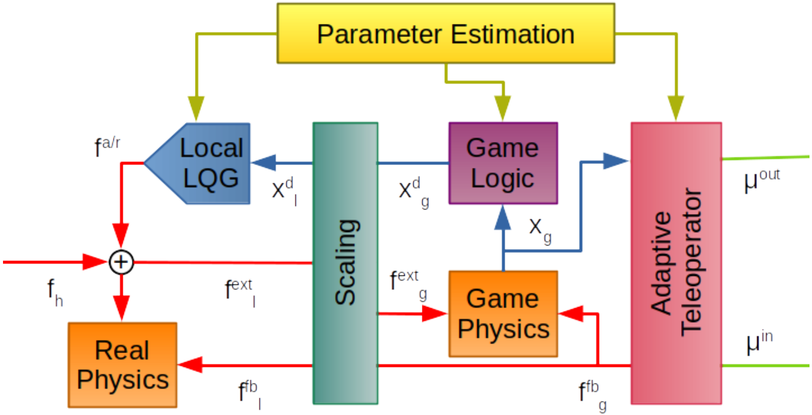
Sections

Distributed Processing Architecture

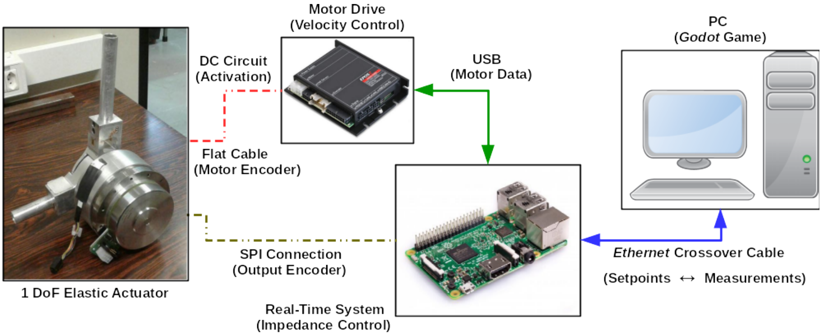


Adapted from Consoni (2017)

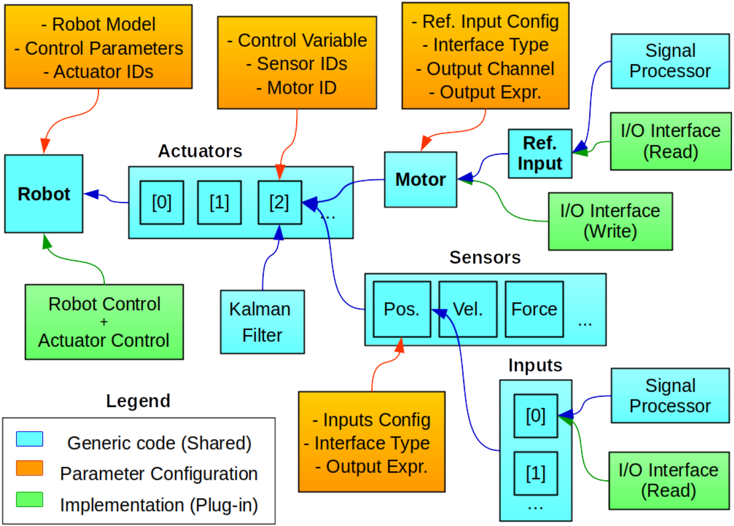
Subsystems [De]coupling



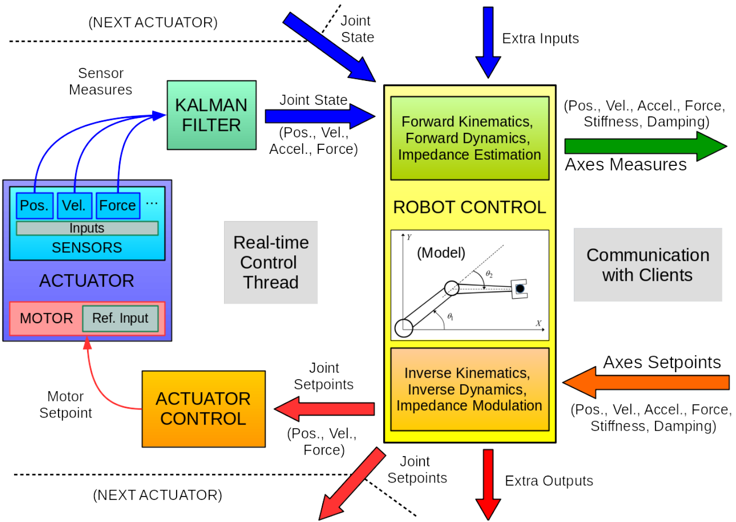
Hardware


Motor Drive
(Velocity Control)
PC
(*Godot* Game)
DC Circuit
(Activation)
USB
(Motor Data)
Flat Cable
(Motor Encoder)
SPI Connection
(Output Encoder)
Ethernet Crossover Cable
(Setpoints ↔ Measurements)
1 DoF Elastic Actuator
Real-Time System
(Impedance Control)

Robotic Control (*Architecture*)

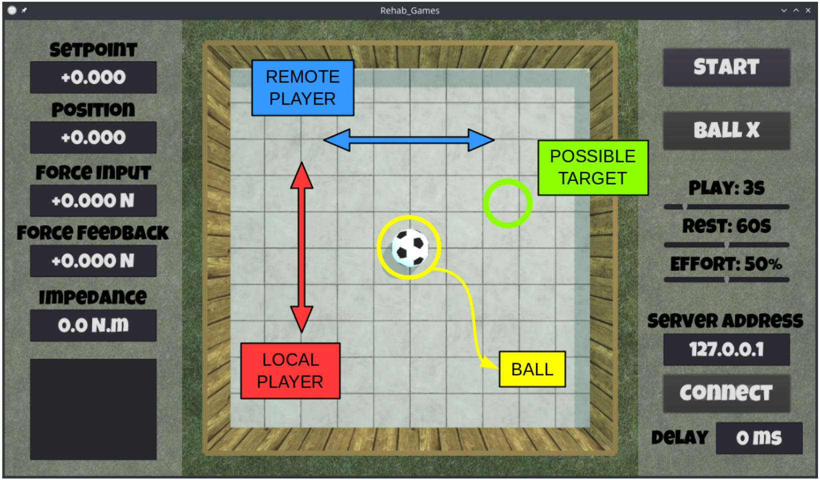


Robotic Control (Operation)



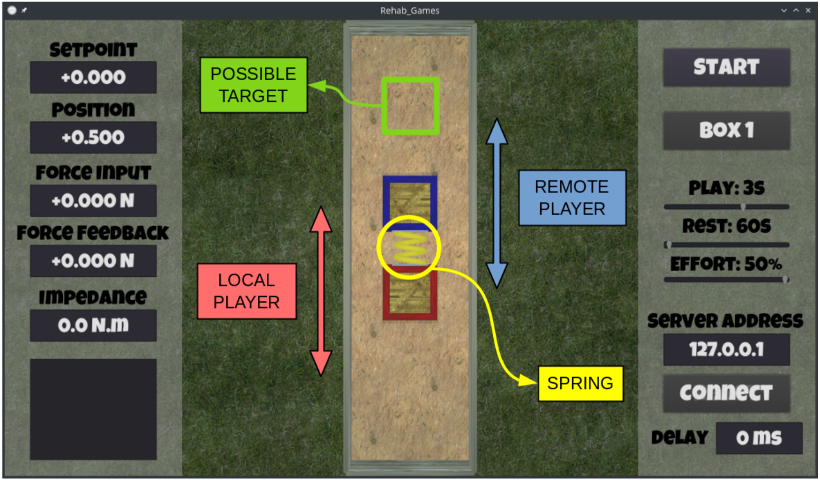
Telerehabilitation Games

- Co-activity/Competition



Telerehabilitation Games

- Collaboration/Competition

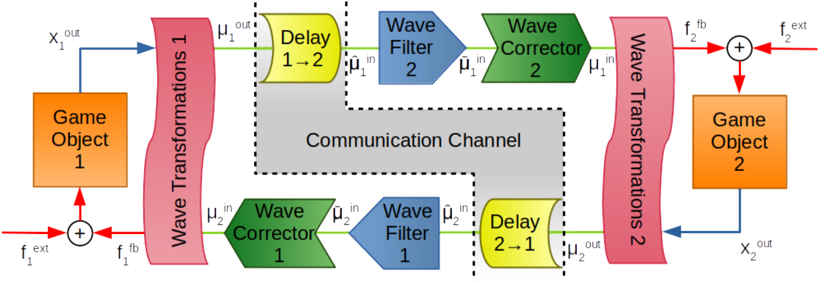


Telerehabilitation Games

- Developed for *Godot Engine*
- Framework created for greater code reuse
- Client (local) and server (semi-authoritative) modes
- Delay handling
  - Latency estimations (half of RTT)
  - Application of nterchangeable correction algorithms
    - Prediction w/ *Kalman* filter
    - Wave variables (WV) w/ correction
    - LQG w/ direct force feedback reflection (LQG-FFB)

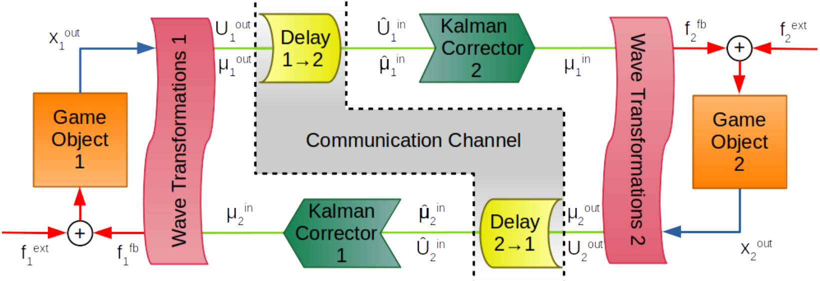
Teleoperation Algorithms

- Wave variables w/ correction



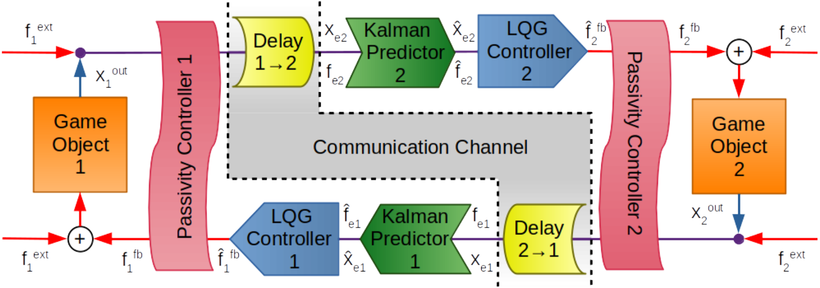
Teleoperation Algorithms

- Wave variables w/ correction (alternative)



Teleoperation Algorithms

- LQG-FFB w/ prediction

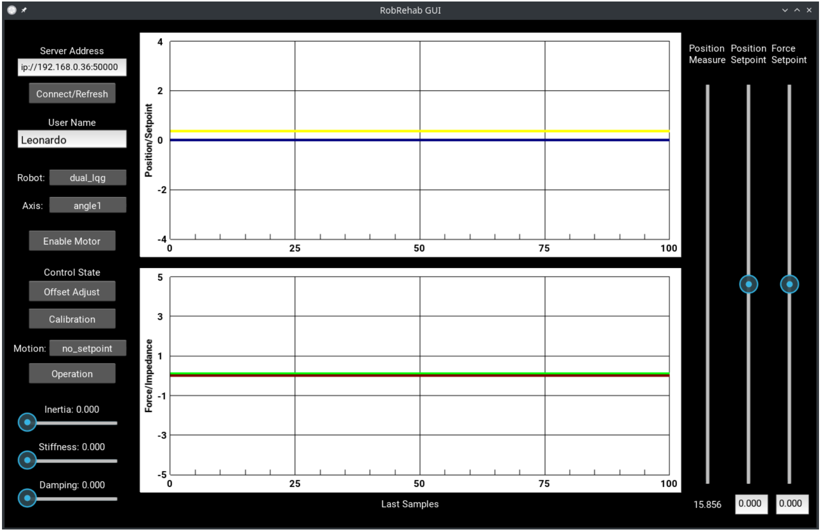


Auxiliary Interfaces

- Calibration screen

Auxiliary Interfaces

- Visualization GUI



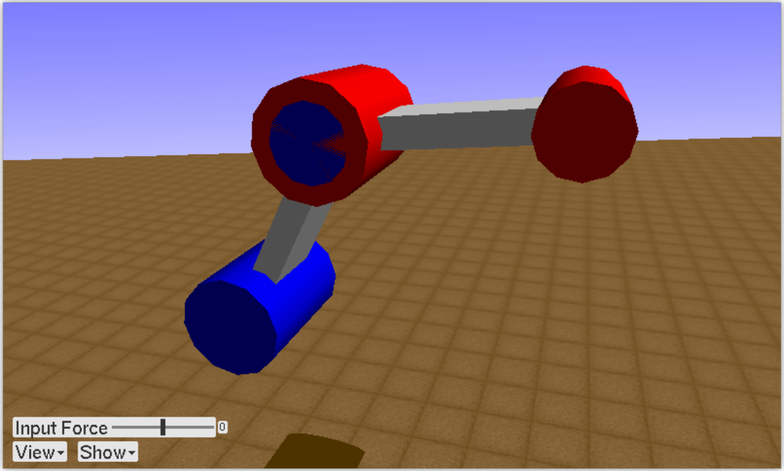
Intended Innovation

- Online identification
  - Local mechanical properties
  - Network delay estimation
  - Suplements static formulations and offline procedures
- User effort estimations
  - Improved local AAN control adaptation
  - Actions modeled as explicit input instead of disturbance
- Input/output signal scaling
  - Decoupling real environment from virtual world
  - Straightforward switching of external devices
- Subsystems recoupled via linear model (impedance estimations)

Sections

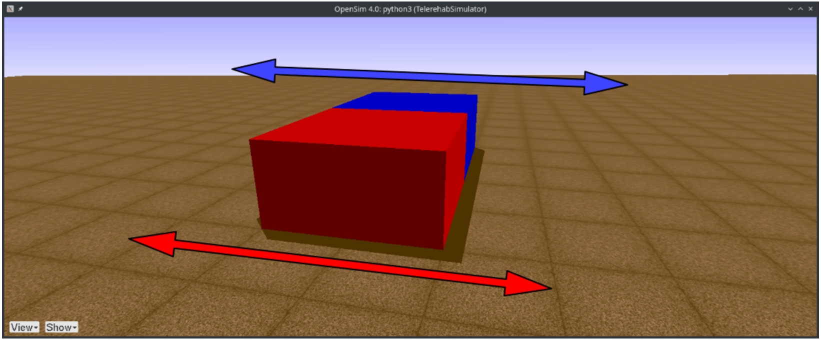
Simulations

- *OpenSim* Simulator



Simulations

- *OpenSim* Simulator

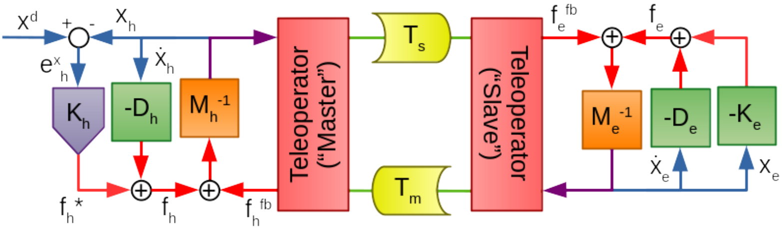


Simulations

- Simulated inputs/reactions
- Interative mode
- WV vs LQG-FFB
- Effects of auxiliary techniques: prediction and TDPC
- Artificial lag (200 +/- 100 ms)
- Testing rounds of 40s (2000 samples w/ 0.02s time step)
- Data recorded at the "patient" terminal side
- Passivity and transparency indexes

Simulations

- Passive resistance



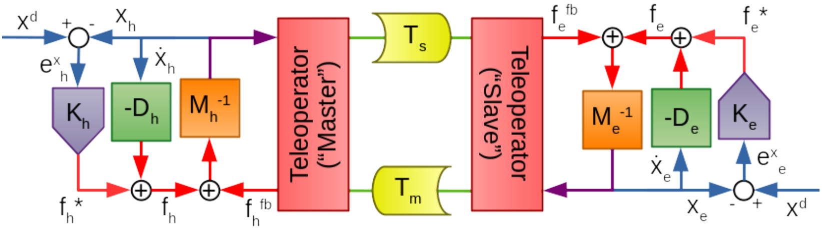
Simulations

- Passive resistance

	Tracking error	Inertia error	Damping error	Stiffness error	PM	TM
Wave variables (no prediction)	0.006	0.613	1.726	4.476	0.046	0.106
LQG-FFB w/o M-TDPC (no prediction)	0.010	0.269	1.543	3.311	0.011	**0.070**
LQG-FFB w/ M-TDPC (no prediction)	0.025	0.150	0.404	6.121	0.046	0.094
Wave variables (prediction)	0.007	0.865	0.930	3.993	**0.032**	0.119
LQG-FFB w/o M-TDPC (prediction)	0.010	0.214	1.693	3.275	-0.004	0.082
LQG-FFB w/ M-TDPC (prediction)	0.025	0.142	0.495	6.174	0.045	0.095

Simulations

- Coordination assistance



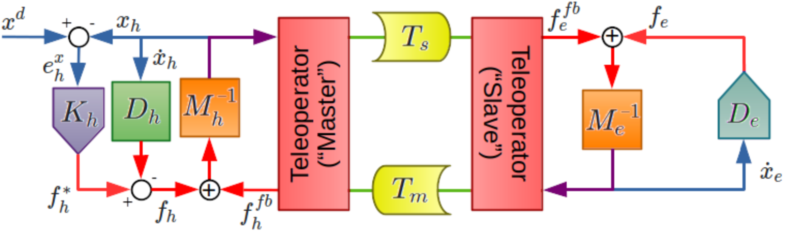
Simulations

- Coordination assistance

	Tracking error	Inertia error	Damping error	Stiffness error	PM	TM
Wave variables (no prediction)	0.009	0.738	0.000	1.721	-0.179	0.299
LQG-FFB w/o M-TDPC (no prediction)	0.013	0.268	0.000	0.082	-0.318	**0.121**
LQG-FFB w/ M-TDPC (no prediction)	0.013	0.309	0.000	0.094	**-0.303**	**0.121**
Wave variables (prediction)	0.009	1.083	0.000	1.004	-0.323	0.340
LQG-FFB w/o M-TDPC (prediction)	0.012	0.180	0.066	0.150	-0.495	0.179
LQG-FFB w/ M-TDPC (prediction)	0.014	0.246	0.041	0.170	-0.422	0.162

Simulations

- Power assistance



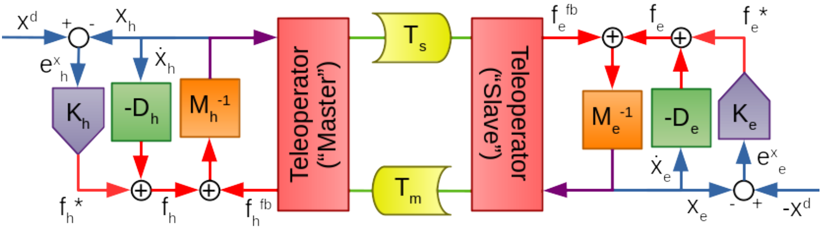
Simulations

- Power assistance

	Tracking error	Inertia error	Damping error	Stiffness error	PM	TM
Wave variables (no prediction)	0.008	0.623	0.577	0.107	-0.047	**0.214**
LQG-FFB w/o M-TDPC (no prediction)	708.47	0.947	0.000	0.004	-3.23e8	2.71e3
LQG-FFB w/ M-TDPC (no prediction)	0.111	0.732	0.060	0.000	-3.265	0.429
Wave variables (prediction)	0.016	0.773	0.000	0.000	**-0.439**	0.255
LQG-FFB w/o M-TDPC (prediction)	7.37e4	0.963	0.000	0.105	-4.29e12	2.32e5
LQG-FFB w/ M-TDPC (prediction)	0.129	0.775	0.000	0.202	-3.477	0.519

Simulations

- Active resistance



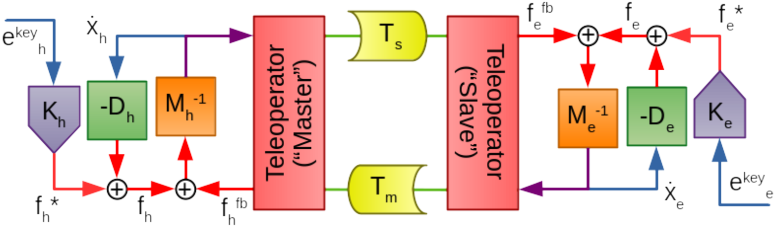
Simulations

- Active resistance

	Tracking error	Inertia error	Damping error	Stiffness error	PM	TM
Wave variables (no prediction)	0.017	0.529	0.000	2.241	-0.168	0.166
LQG-FFB w/o M-TDPC (no prediction)	0.026	0.199	0.305	8.642	-0.067	**0.085**
LQG-FFB w/ M-TDPC (no prediction)	0.035	0.411	3.650	22.397	0.007	0.131
Wave variables (prediction)	0.019	0.451	0.000	2.646	**-0.162**	0.169
LQG-FFB w/o M-TDPC (prediction)	0.025	0.186	0.247	4.553	-0.094	0.104
LQG-FFB w/ M-TDPC (prediction)	0.036	0.403	2.240	16.019	0.005	0.131

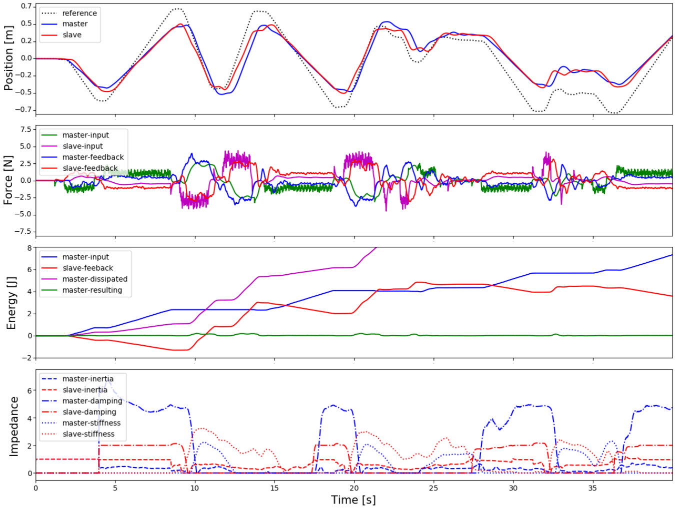
Simulations

- User input



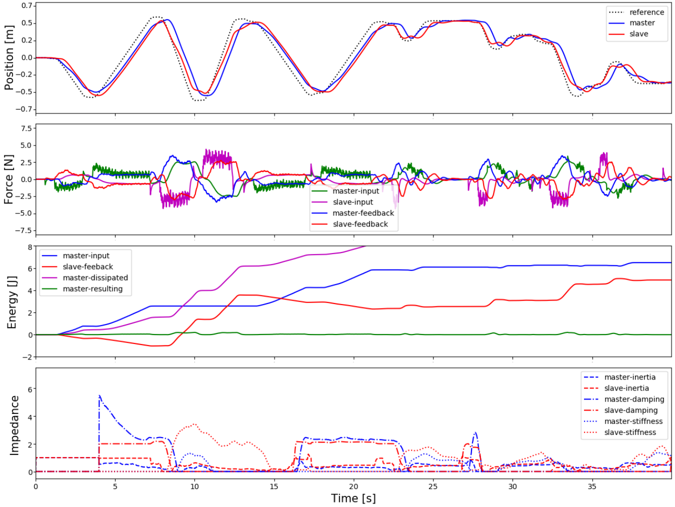
Simulations

- User input - WV w/o prediction



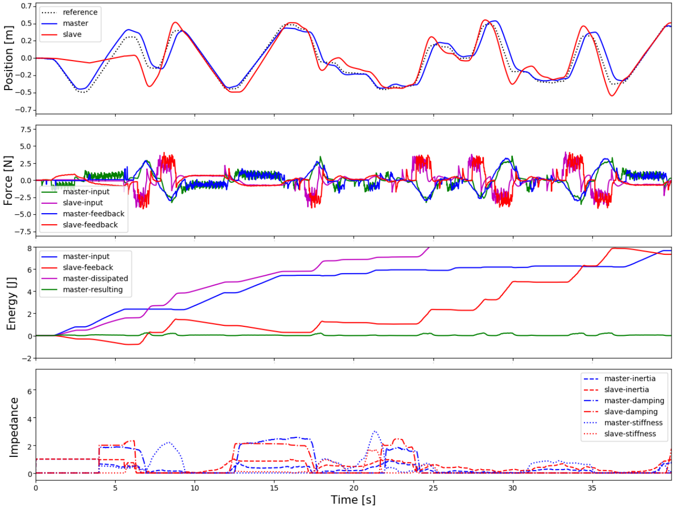
Simulations

- User input - WV w/ prediction



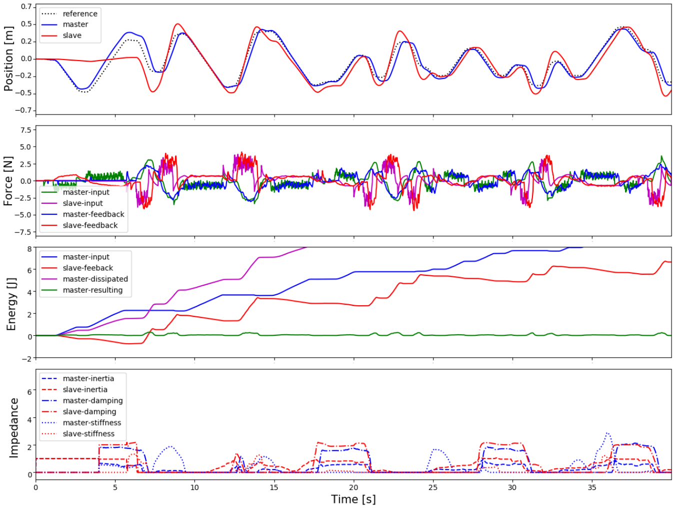
Simulations

- User input - LQG-FFB w/o prediction



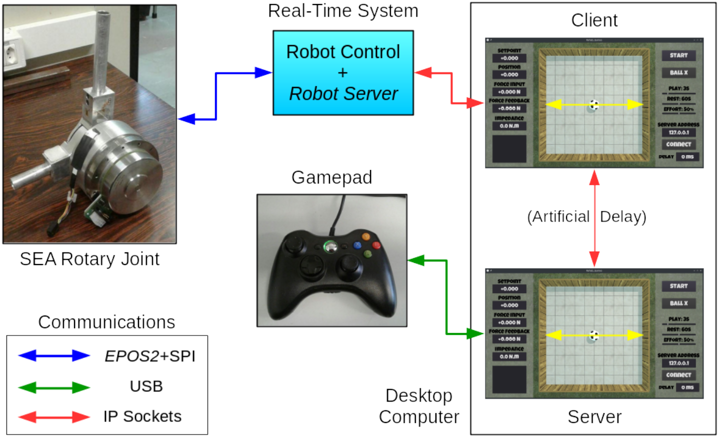
Simulations

- User input - LQG-FFB w/ prediction



Laboratory Experiments

- General layout

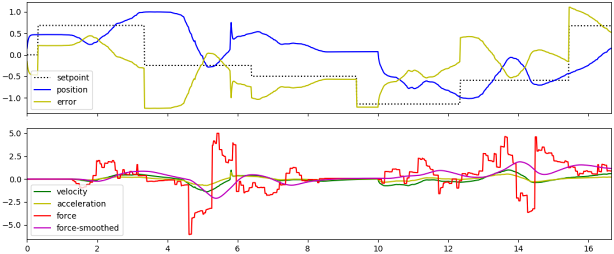


Laboratory Experiments

- WV w/ prediction vs LQG-FFB w/ TDPC
- Delay (100 +/- 50 ms) and packet loss (5%) induced on network interfaces (netem)
- Testing rounds of 50s (2500 samples w/ 0.02s time step)
- Data recorded at the robot terminal side
- Additional logs:
  - Offline and online identification
  - Stiffness vs user force correlation

Laboratory Experiments

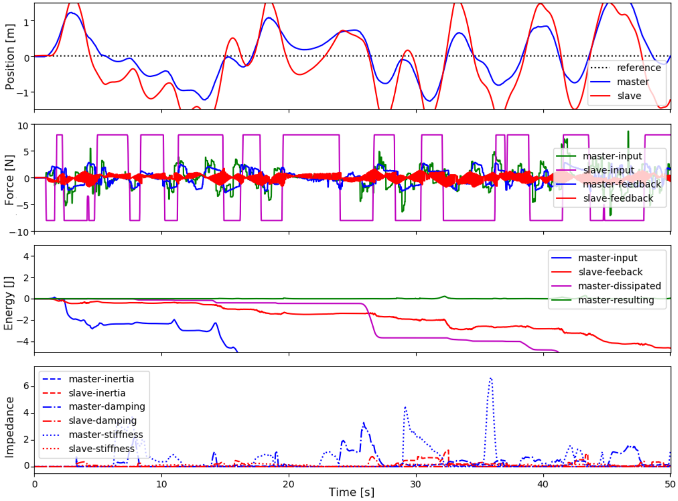
- Position x force measurements and impedance estimations



	$\hat{K}^{avg}_{cal}$	$\hat{K}^{avg}_{op}$	$\hat{K}^{avg}_{op}$ / $\hat{K}^{avg}_{cal}$	$\hat{D}^{avg}_{cal}$	$\hat{D}^{avg}_{op}$	$\hat{D}^{avg}_{op}$ / $\hat{D}^{avg}_{cal}$	$corr(f, \hat{K})$
Test round 1	5.491	9.317	1.697x	4.228	5.238	1.239x	1.246
Test round 2	3.024	5.534	1.830x	1.469	2.992	2.037x	1.360
Test round 3	2.994	6.957	2.323x	1.462	2.338	1.600x	1.458
Test round 4	2.376	6.641	2.795x	2.090	2.446	1.170x	1.124

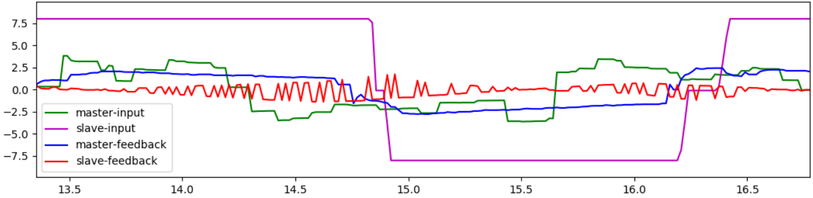
Laboratory Experiments

- WV w/ prediction and offline identification



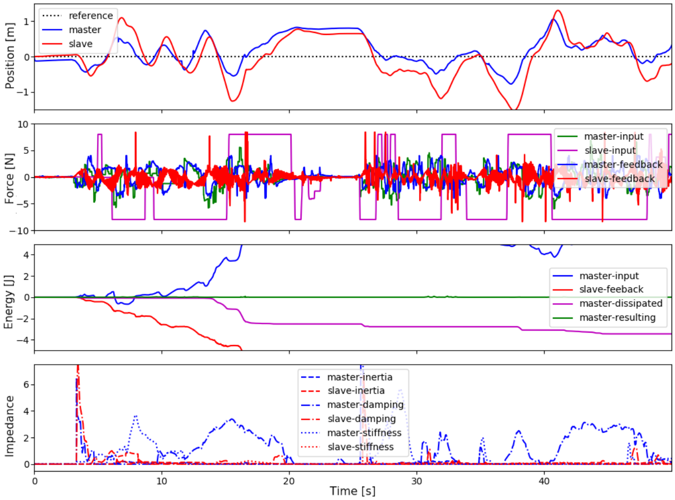
Laboratory Experiments

- WV w/ prediction and offline identification



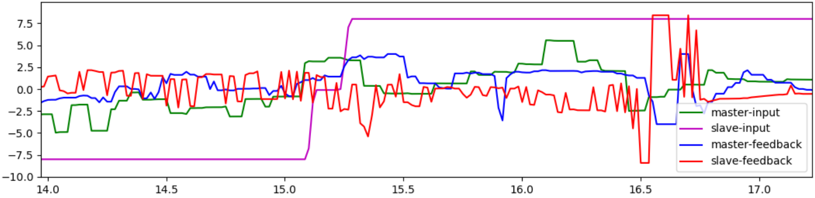
Laboratory Experiments

- WV w/ prediction and online identification



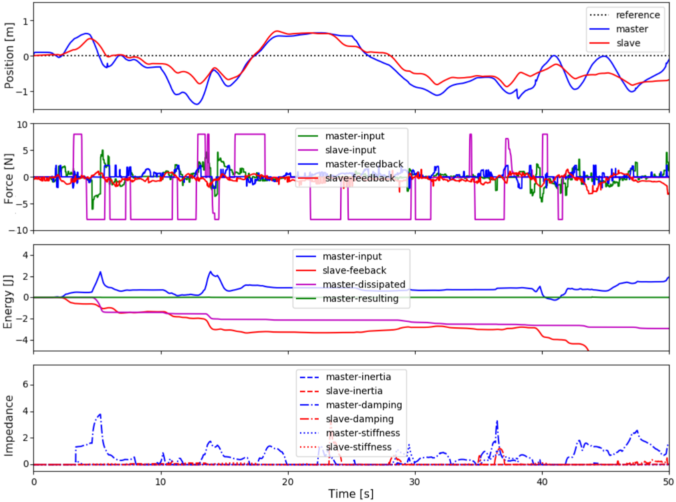
Laboratory Experiments

- WV w/ prediction and online identification



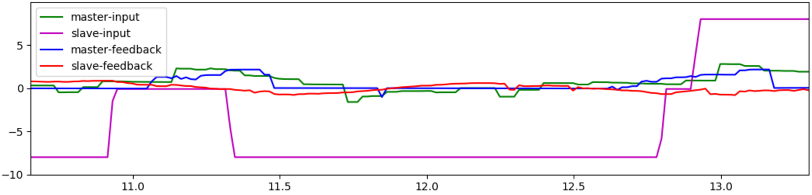
Laboratory Experiments

- LQG-FFB w/ TDPC and offline identification



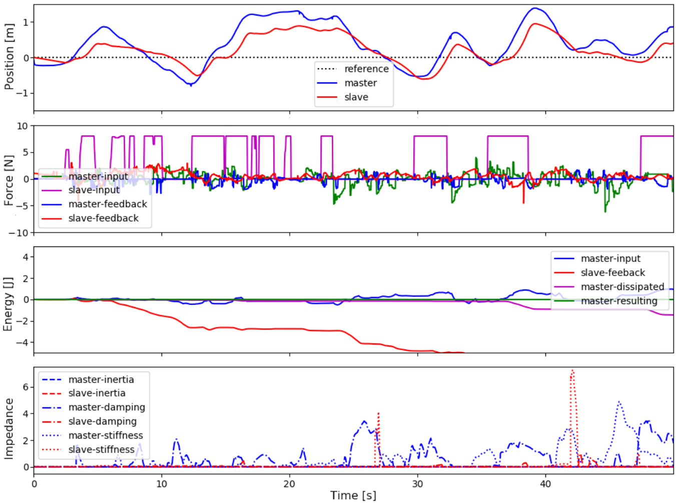
Laboratory Experiments

- LQG-FFB w/ TDPC and offline identification



Laboratory Experiments

- LQG-FFB w/ TDPC and online identification



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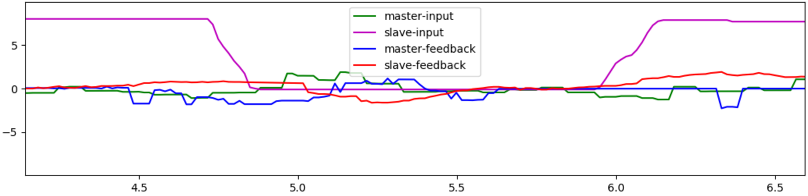

Sections

Discussion of Results

- Partially expected outcome
- Wave variables have better contact behaviour
- LQG-FFB works better for coordination assistance
- *Kalman* prediction improves wave variables
- Passivity control ensures LQG-FFB stability
- Online identification improves transparency
- LQG-FFB presents smoother force reflection
- Caveat: Low-quality force measurements hindered the experiment

Issues to be Addressed

- More robust contact force estimations
- Remote teaching/learning effectiveness analysis
- Difficulty balancing and its evaluation
- Internal control loop optimization
- Is direct force exchange actually needed?
- VoIP and AR/VR
- Low-cost devices (home care)

Additional Works

- Papers published in conferences
  - 5º ENEBI: Consoni and Siqueira (2015)
  - 23rd COBEM: Consoni, Santos and Siqueira (2015)
  - 6th BioRob: Consoni et al. (2016)
  - 1º SipGEM: Consoni and Siqueira (2016)
  - 15th ICORR: Consoni, Siqueira and Krebs (2017)
- Open source code available (GitHub)
- Documentation (Doxygen and GH Pages)

Acknowledgements

FAPESP

CAPES

CNPq