Human-Robot Cooperation with Mechanical Interaction Based on Rhythm Entrainment

—Realization of Cooperative Rope Turning—

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1. Introduction
2. Cooperative Rope Turning
3. Frequency Synchronization by Entrainment
4. Phase Tuning based on Energy Transfer
5. Experiments of Rope Turning
6. Conclusion

1. Introduction

Robot Motion based on Rhythm Entrainment

- Bio-mimetic Approach
- for Flexible and Robust Motion Generation

Bipedal Locomotion [Taga 91] [Miyakoshi 98],
Quadruped Locomotion [Kimura 00]
Rhythmic Arm Movements [Williamson 98], …

↓ Application to Cooperation

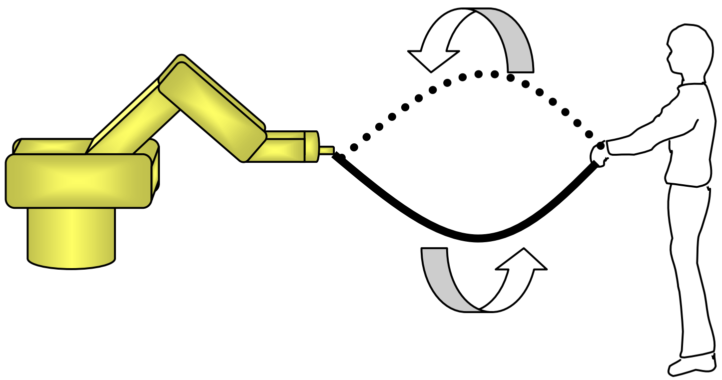
Support of Human Walking [Miyake 94]
Cooperative Transportation [Mukaiyama 99]
Imitation of Human Movement [Kotosaka 00]

…only simulation results
or cooperation without mechanical interaction

Objective

Achieve a human-robot cooperative task with mechanical interaction based on rhythm entrainment

Example Task: Cooperative Rope Turning



Approach to Cooperative Rope Turning

Problems to be solved for human-robot cooperation

Frequency Synchronization

⇨ Rhythm Entrainment by LPLL

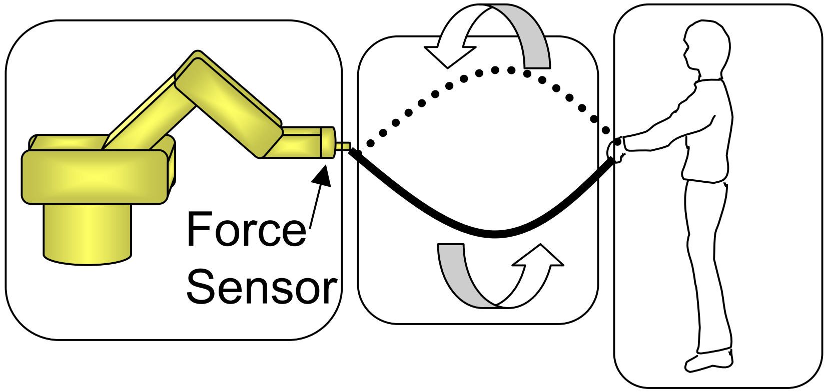
(Linear Phase-Locked Loop)

Tuning of Phase Difference

⇨ Adaptation by Energy Transfer Control

2. Cooperative Rope Turning

Human-Robot Cooperative Rope Turning

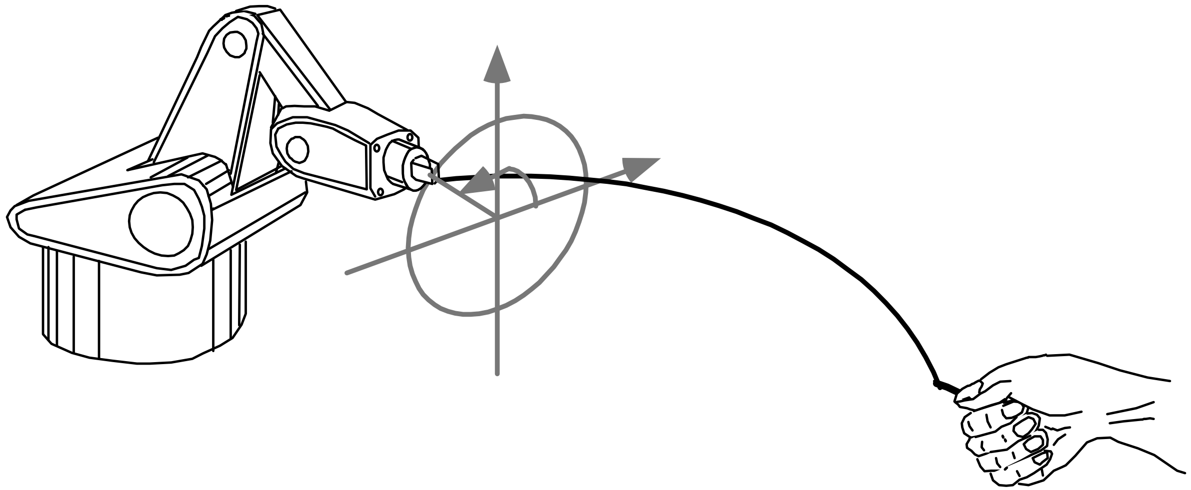


Keep Rope Turning
without Slackening of Rope

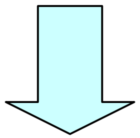
Why rope turning?

1. It is a simple periodic task.
2. It requires mechanical coordination.
3. We can measure and control energy transfer with a force sensor.

Cooperative Rope Turning in This Research

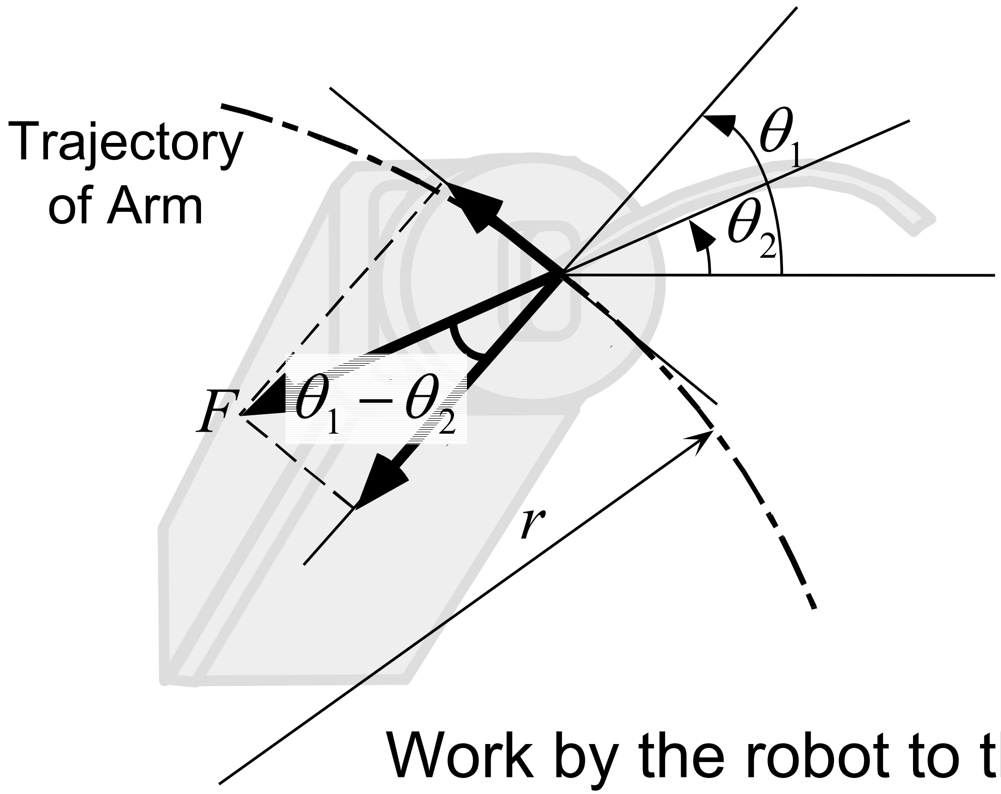


The path of the endpoint of the robot is limited to a circle



Robot motion is described
only by its <u>frequency</u> and <u>phase</u>

A Simple Model for Rope Turning



r : radius of circular movement of arm = 30 [mm]
F : magnitude of the force applied to rope by arm
Δt : sampling time
θ_1 : phase of robot motion
θ_2 : phase of rope

Work by the robot to the rope:

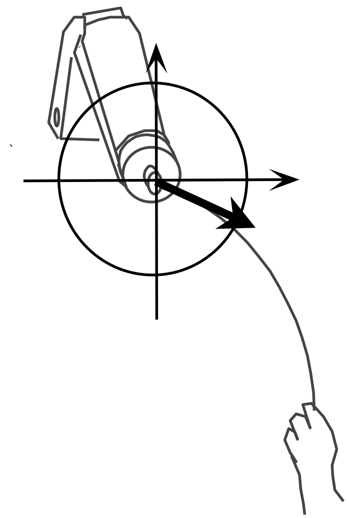
$$\Delta W = Fr\dot{\theta}_1 \sin(\theta_1 - \theta_2) \cdot \Delta t$$

The robot can control energy transfer by adjusting its phase (θ_1)

3. Frequency Synchronization by Entrainment

Synchronization of Robot Frequency to Rope Frequency

• Phase of rope can be measured by Force Sensor



Robot can follow rope motion

by synchronization to force signal

• Synchronization to force signal by entrainment

➡ Software LPLL (Linear Phase-Locked Loop)

• Easy parameter tuning

LPLL for Frequency Synchronization

Input: Force Applied to Robot by Rope

Output: Phase of Robot Motion

If the input is ...

- in the lock range of LPLL
  - ⇨ Locked to the input frequency
- out of the lock range of LPLL
  - ⇨ Oscillation in its inherent frequency

⇩

Robust Frequency Synchronization
for Cooperative Rope Turning

4. Phase Tuning Based on Energy Transfer

Application of Adaptation Theory

Adaptation Theory [Ito 99]

Adaptation: “a process that decreases unnecessary subsystem interaction”

⇩

Cooperation by decreasing unnecessary <u>subsystem interaction</u>

↑

Energy Transfer

Phase Tuning of Robot Motion

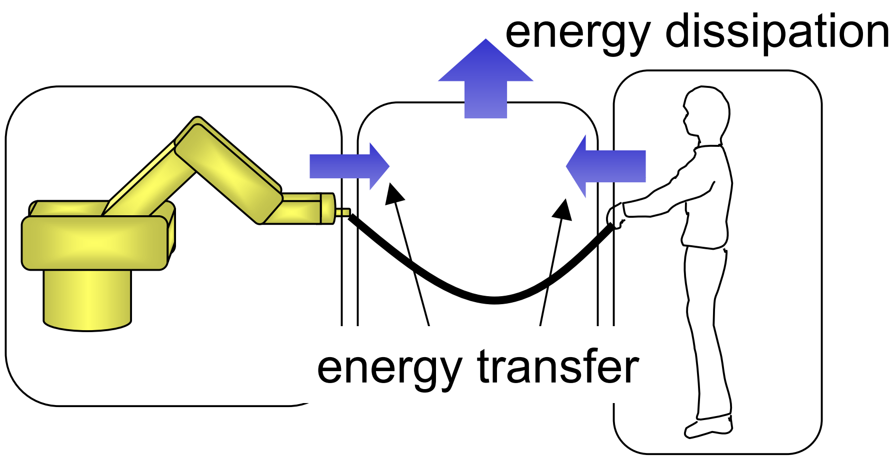
Feedback control of phase
to achieve desired energy transfer

Forward phase shift

⇨ decrease energy transfer from robot to rope

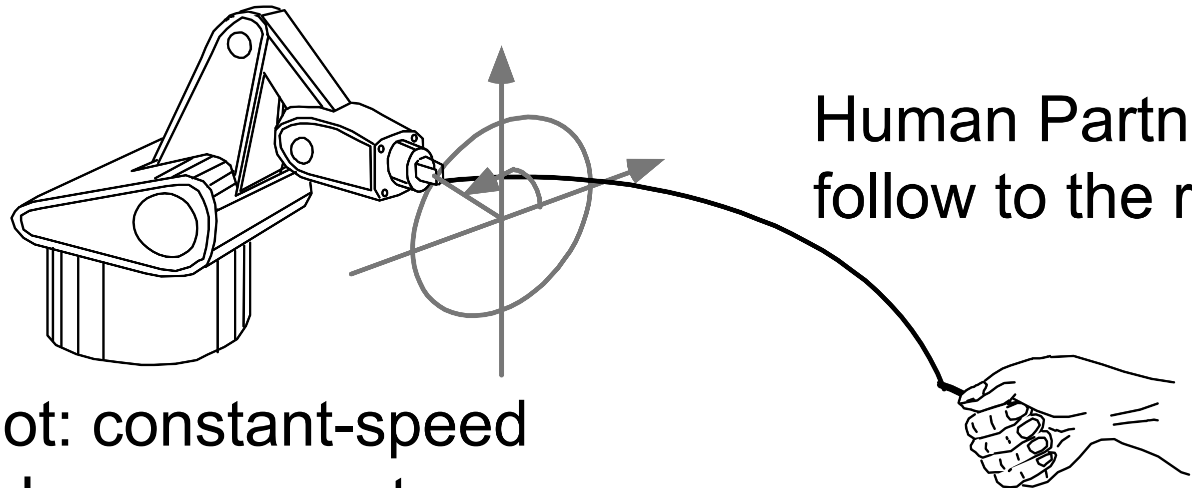
Backward phase shift

⇨ increase energy transfer



Desired Energy Transfer

Teaching of Desired Energy Transfer by Human Demonstration

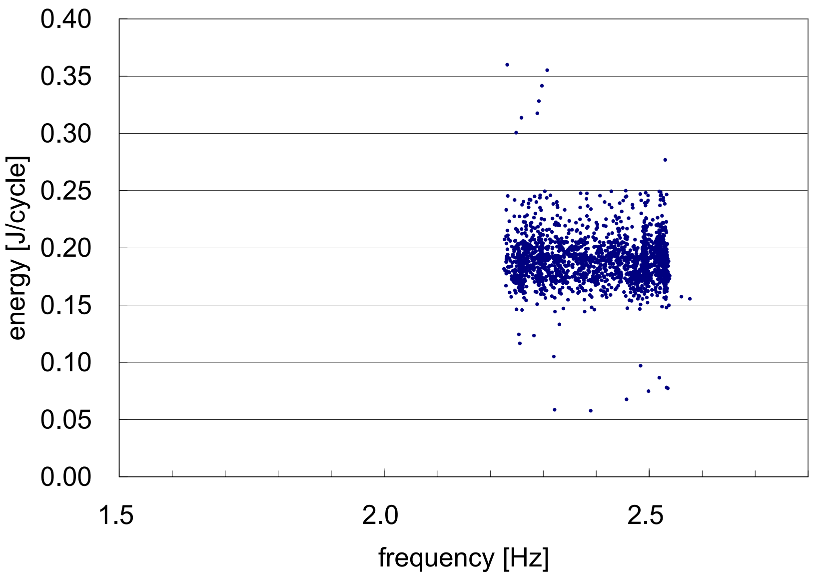


Measured Energy Transfer ⇨ Desired Energy Transfer

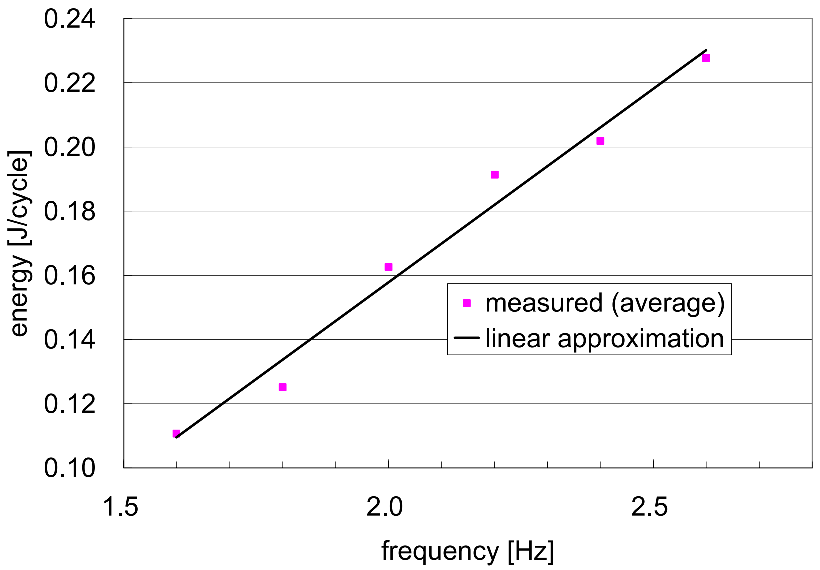
Results of Human Demonstration

Desired Energy Transfer:
Compensation of Energy Dissipation in Rope

➡ Desired energy transfer depends on frequency of rope turning



(a) Measured Energy Transfer at 2.4Hz



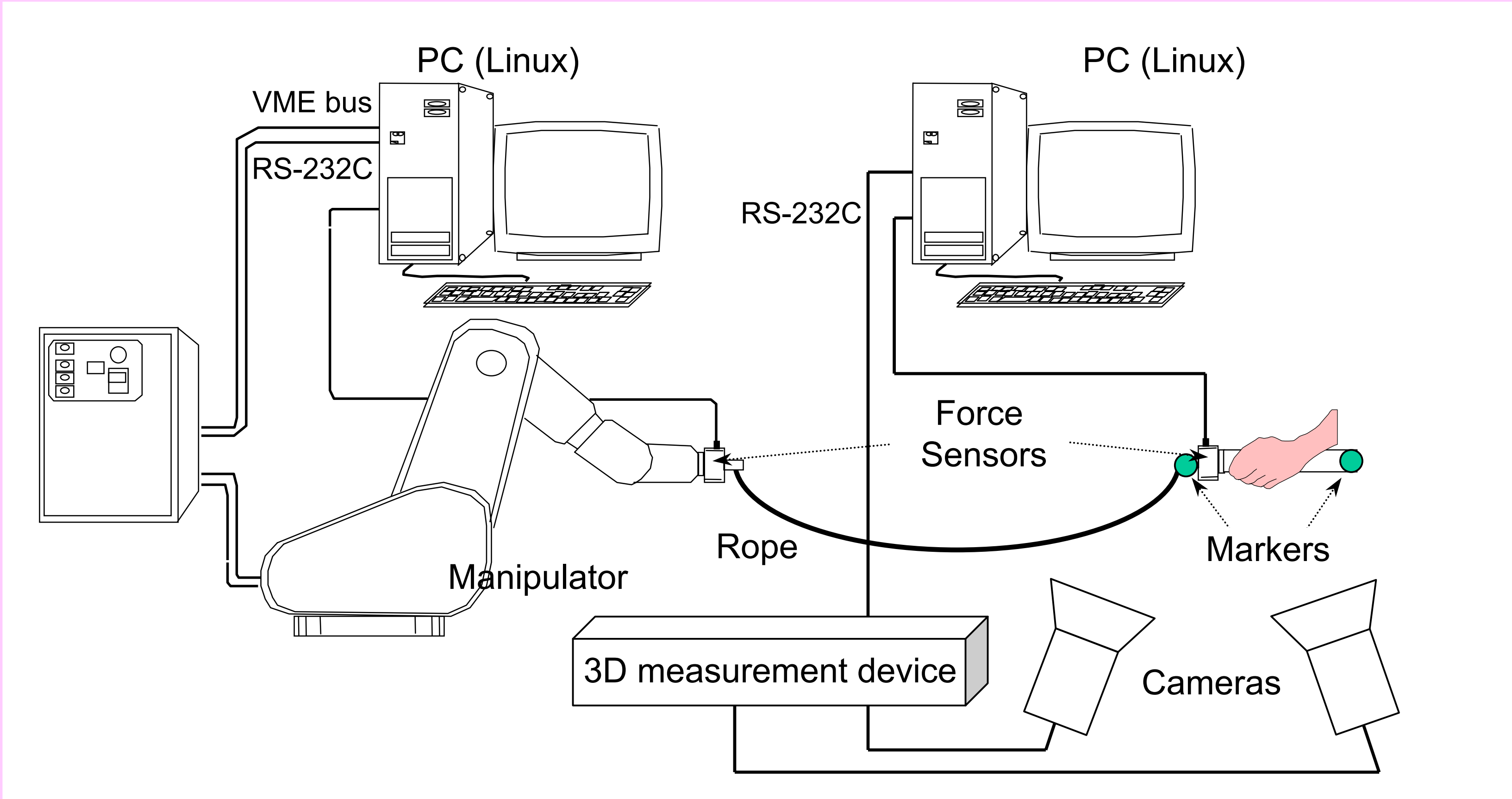
(b) Desired Energy Transfer (Linear Approximation)

5. Experiments of Cooperative Rope Turning

Realization of Cooperative Rope Turning

- Frequency Synchronization using LPLL
- Phase Tuning based on Control of Energy Transfer

Experimental Setup



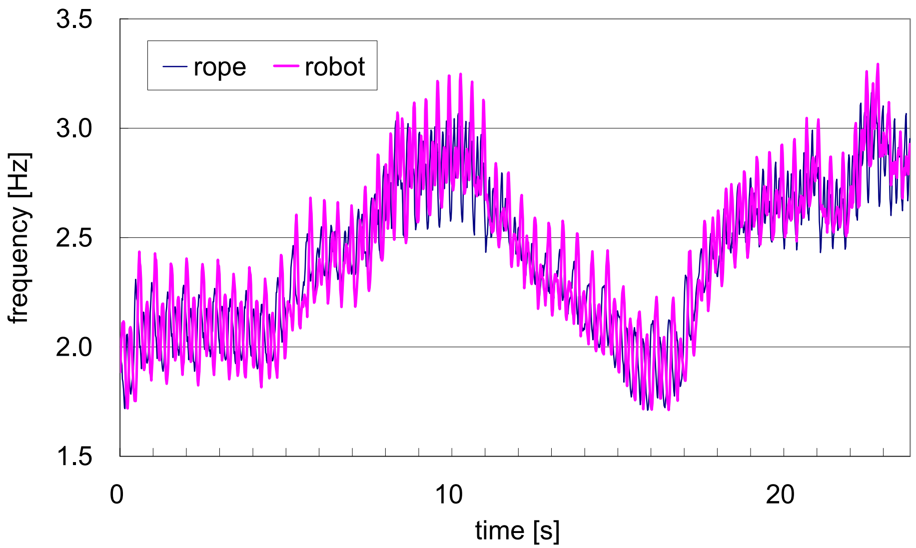
Sampling Time of Force Sensor = 2 [ms]

Control Interval of Manipulator = 16 [ms]

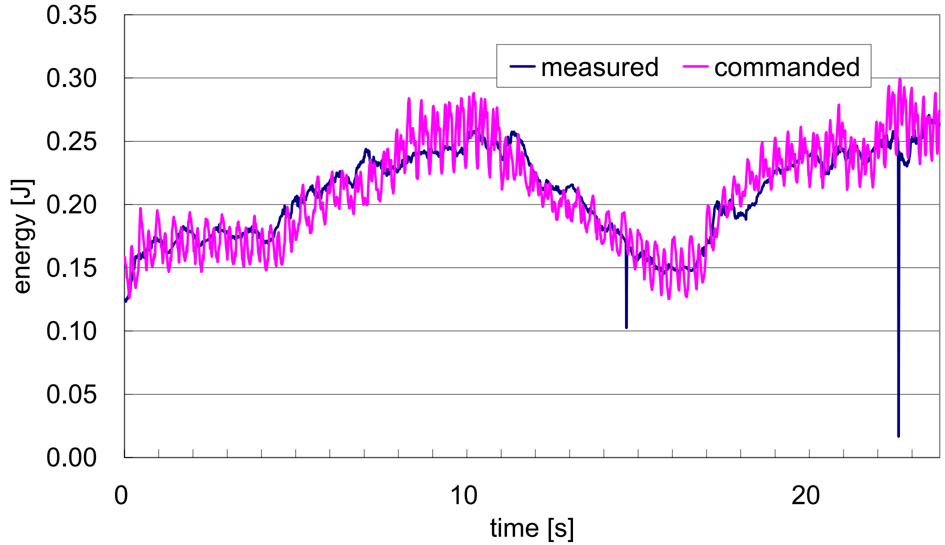
Sampling Interval of 3D measurement = 16 [ms]

Movie: Successful Rope Turning

Experimental Results: Successful Case



Frequency Synchronization



Energy Transfer

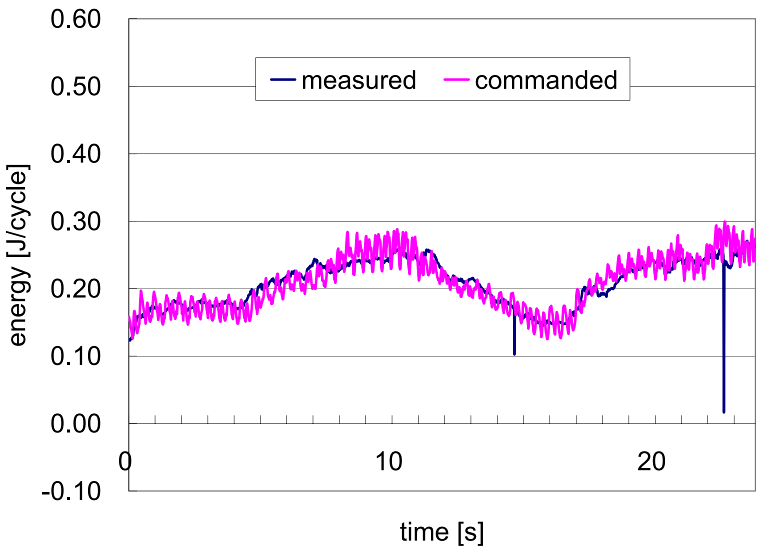
➡ The robot followed the motion of its human partner

Movie: Unsuccessful Rope Turning

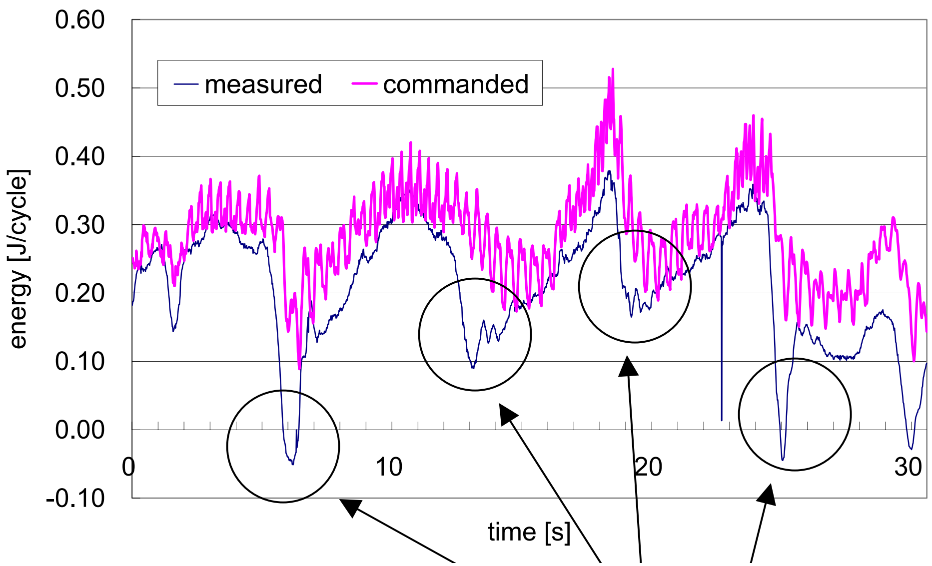
Improper command of energy transfer
(+50% inflated)

Results of Comparison Experiments

Proper / Improper Command of Energy Transfer



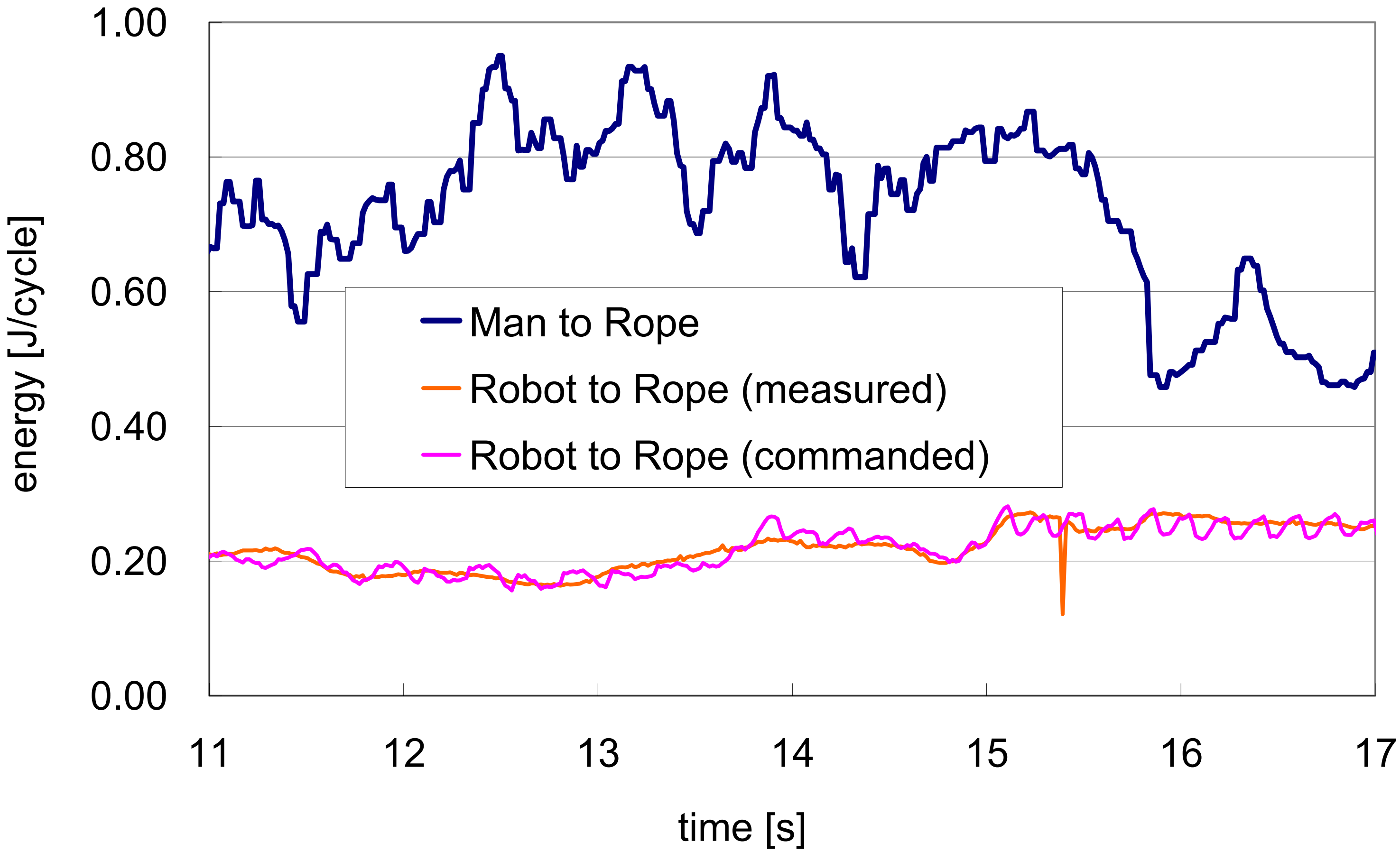
Proper command of energy transfer



<u>Slackening of Rope</u>

Improper command of energy transfer (+50% inflated)

Energy Transfer by Man and Robot



- Stable Cooperative Rope Turning
- More load on human partner

Study on Experimental Results

• Improper value of energy transfer leads to unstable rope turning

⇒ Suggestion of the Importance of Control of Energy Transfer

• Not equal cooperation

The human partner was "working harder" than the robot

6. Conclusion

Conclusion

We realized cooperative rope turning based on rhythm entrainment

- Frequency Synchronization using LPLL
- Phase Tuning based on Control of Energy Transfer

⇒ These approaches may be effective in general for human-robot cooperation with mechanical interaction