

# Human-Robot Cooperation with Mechanical Interaction Based on Rhythm Entrainment — Realization of Cooperative Rope Turning —

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## Abstract

*Adaptation of biological systems can be viewed as decreasing local interaction among subsystems to realize effective cooperation. Conversely, it is important for effective cooperation to evaluate and control local interaction. Based on this idea, we present a method of realizing cooperative rope turning by a man and a manipulator. The rotating motion of the manipulator arm for rope turning can be specified by frequency and phase difference between the arm and the rope. The frequency is determined in real-time by rhythm entrainment using PLL (Phase-Locked Loop). The phase difference is related to the quantity of local interaction, that is, energy transfer from the arm to the rope. Therefore it is controlled to realize desired energy transfer, which is estimated from human demonstration. In the experiment the manipulator can successfully adapt its motion to that of the human partner.*

## 1 Introduction

In cooperation with mechanical interaction, such as cooperative transportation, collaborators should adapt their own motion for their partners each other to achieve a goal of the task. Most robotics researches on cooperative works require task models and control laws specific to each target. If we have general guidelines for cooperative work, the load for modeling the target and designing control laws shall be decreased.

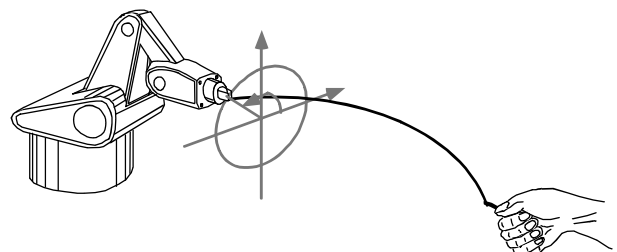
In the context of pattern generation of distributed autonomous systems, Ito et al. defined adaptation of biological systems as “a process that decreases subsystem interaction” [1][2]. In their view, disharmony between subsystems finds expression in unnecessary interaction, so subsystems modify their behavior to decrease interaction locally in adaptation process.

Applying Ito's view to robotic cooperative tasks, it

might be a general principle for cooperation to decrease unnecessary mechanical interaction between partners – interaction force, energy transfer, and so on. The locality of interaction is a merit to achieve cooperation between many subsystems as a decentralized system.

Another candidate of principle in cooperative work is rhythm entrainment. Inspired by the research achievements on the motion pattern generation of humans and animals, many researchers deal with motion generation of robots using entrainment ([3]-[6]). The entrainment between oscillators enables flexible and robust motion for the robots. We expect that rhythm entrainment is also effective to achieve cooperative work with periodic motion. Mukaiyama et al. dealt with cooperative transportation by entrainment [7], however, they presented only simulation results. Miyake et al. [8] [9] and Kotosaka et al. [10] realized human-machine motion synchronization, which was lacking in mechanical interaction. We consider that realization of robotic cooperative tasks with mechanical interaction is very important.

In this paper, we assume that control of mechanical interaction and rhythm entrainment are effective principles for cooperative work. Under those principles, we realize an example task –cooperative rope turning by



**Fig. 1 Cooperative Rope Turning  
by a Man and a Manipulator**

a man and a manipulator. We develop a method of rhythm entrainment with control of mechanical interaction to achieve cooperation, and verify the validity of the above assumption.

## 2 Cooperative Rope Turning

Consider cooperative rope turning by a man and a manipulator, shown in Fig. 1. Suppose that the man does not adapt himself to the motion of the manipulator on purpose, and his motion often fluctuates. The objective of this task is that the manipulator keeps the rope turning without slack by adapting to its human partner. We choose the task as a good example for the following reason:

- It is a simple periodic task.
- It requires mechanical coordination.
- We can measure and control energy transfer between subsystems as mechanical interaction.

For simplicity, we limit the motion of the endpoint of the manipulator to circular movement of radius  $r$ . In Fig. 2, we describe a simple model of mechanical interaction between the manipulator arm and the rope. The endpoint motion can be represented by its frequency  $f = \pi$  and phase  $\theta$ . For successful rope turning, the manipulator has to tune its frequency and phase according to the motion of its human partner. In the next section, we introduce a method to achieve rhythm entrainment from local information, i.e., data of position of the arm and force applied to the arm.

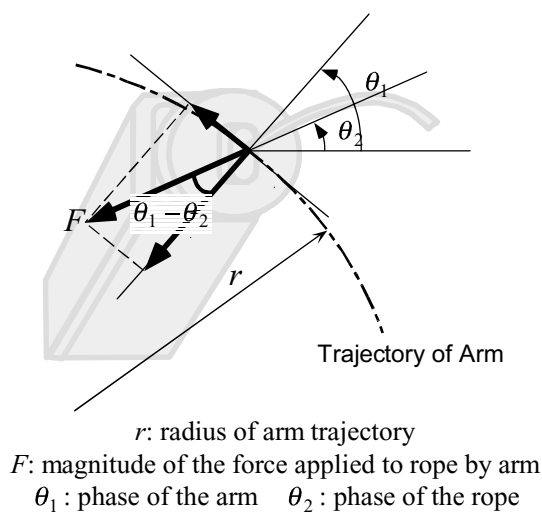


Fig. 2 Simple Model of Arm-Rope Interaction

## 3 Rhythm Entrainment

### 3.1 Frequency Synchronization Using LPLL

Cooperative rope turning clearly requires the manipulator to equalize its frequency of motion with that of the rope. Because phase of the rope  $\theta$ , can be measured as the direction of rope force that pulls the manipulator, we can achieve frequency synchronization using force signals. For robust synchronization, we utilize entrainment of oscillators. For easy parameter tuning, we adopt a software LPLL (Linear Phase-Locked Loop) [11]. An advantage of PLLs over other nonlinear oscillators (for example, well-known Matsuoka's one [11]) is that design methodology is established for desired specifications, such as lock range, in the engineering field.

Fig. 3 is the block diagram of the software LPLL. We denote the input signal of LPLL at the  $n$ -th sampling by  $u_1(n)$ , and output phase signal as  $\phi_-(n)$ . Note that  $u_1$  is the force signal and  $\phi_-$  corresponds to the phase of the manipulator in our application. Then the output of DCO (Digital Controlled Oscillator) is:

$$u_2(n) = \begin{cases} 1 & \text{if } \left( \frac{3}{5}\pi + 2(k-1)\pi \leq \phi_2(n) \leq -\frac{2}{5}\pi + 2k\pi \right) \\ -1 & \text{if } \left( -\frac{2}{5}\pi + 2k\pi < \phi_2(n) < \frac{3}{5}\pi + 2k\pi \right) \end{cases} \quad (k: \text{interger}) \quad (3.1)$$

The phase detector in Fig. 3 is just a multiplier. We can write its output signal as:

$$u_d(n) = K_d u_1(n) u_2(n) \quad (3.2)$$

where  $K_d$  is detector gain. We adopt a first-order digital filter for the low pass filter described as:

$$u_f(n) = -a_1 u_f(n-1) + b_0 u_d(n) + b_1 u_d(n-1) \quad (3.3)$$

where  $a_1$ ,  $b_0$  and  $b_1$  are filter coefficients. Finally, total phase of the DCO output signal is:

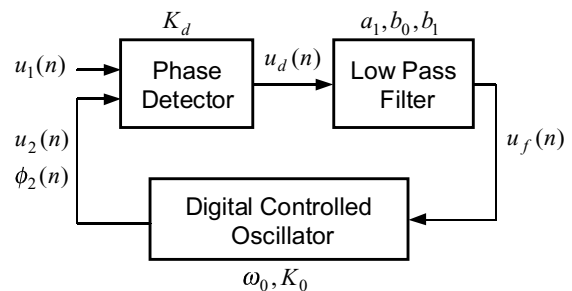


Fig. 3 Block Diagram of Software LPLL

$$\phi_{-}(i) + \phi_{-}(n) \omega + \phi_0 u_f(n)]T \quad (3.4)$$

where  $\omega$  is the center angular frequency of the DCO,  $K_0$  is the DCO gain, and  $T$  is the sampling interval. The above calculation is implemented as a C-language program.

### 3.2 Phase Tuning Based on Control of Energy Transfer

Though LPLL enables frequency synchronization, it is not enough to achieve successful rope turning. Proper control of phase difference between the manipulator and the rope is essential to mechanical coordination.

Using the simplified model in Fig. 2, we can denote the work  $\Delta$  by the manipulator to the rope in infinitesimal time  $\Delta t$  as follows:

$$\Delta = \dots \sin(\theta_1 - \theta_2) \dots \quad (3.5)$$

Equation (3.5) means that the bigger the phase lead  $\theta_1 - \theta_2$  is, the more energy transfer from the manipulator to the rope is. Therefore, the manipulator can control the quantity of energy transfer, i.e., interaction between subsystems, by adjusting its phase  $\theta$ .

As we have mentioned, we attempt to achieve cooperation by decreasing the mechanical interaction as possible. Minimum energy transfer between the manipulator and the rope for successful rope turning means that the manipulator transfers energy only for its allotment of the compensation of dissipation in the rope. If the desired quantity of energy transfer for the manipulator is known, we can use feedback control of energy transfer through the phase adjustment for successful rope turning. We adopt a simple feedback control law as follows:

$$\theta = \phi + K_p (E_{\text{desired}} - E) \quad (3.6)$$

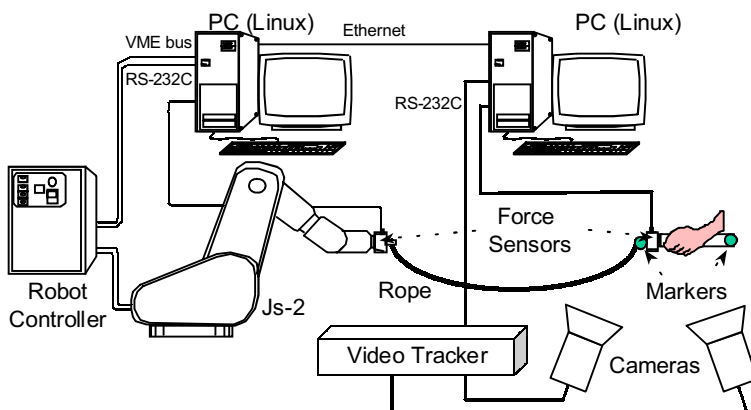
where  $K_p$  is feedback gain.  $E_{\text{desired}}$  and  $E$  is the desired and measured quantity of energy transfer over a current cycle, respectively. We determine  $E_{\text{desired}}$  by human demonstration, which will be described in the subsection 4.2.

## 4 Experiments of Cooperative Rope Turning

### 4.1 Experimental Setup

Our experimental setup for cooperative rope turning by a man and a manipulator is illustrated in Fig. 4. We use a 6-d.o.f. manipulator “Js-2” (by Kawasaki Heavy Industry), which is position-controlled at 16 [ms] interval. A force sensor is located at the endpoint of the manipulator and samples 6-axis force/torque data at 2.3 [ms] interval. We can measure the energy transfer between the manipulator and the rope by sampled force data and encoder data of the manipulator, by compensating the effect of gravitational and inertial force. A Linux PC controls the manipulator and the force sensor.

To analyze energy transfer from the man to the rope, another force sensor and a 3D motion measurement system are installed. The motion measurement system consists of two CCD cameras with 640x416 resolution and an arithmetic unit, called “VideoTracker G280” by OKK Inc. The system can measure 3D coordinates of reflecting markers attached to a grip of the rope at 16 [ms] interval to a precision of about 1.0 [mm]. By these apparatuses, another Linux PC collects data of energy transfer between the man and the rope for analysis of the



(a) Schematic View of Experimental Setup



(b) A Scene of Cooperative Rope Turning

Fig. 4 Experimental System for Cooperative Rope Turning

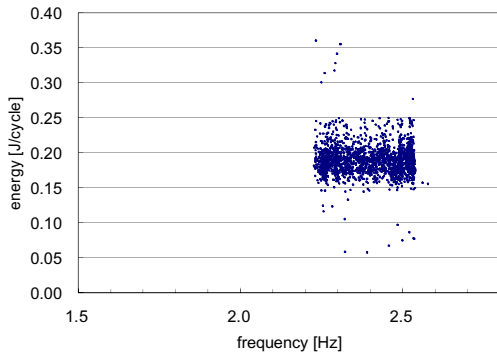
experimental results. Note that the control of the manipulator is achieved by only its own internal encoders and the force sensor attached to it.

#### 4.2 Teaching of Desired Energy Transfer by Human Demonstration

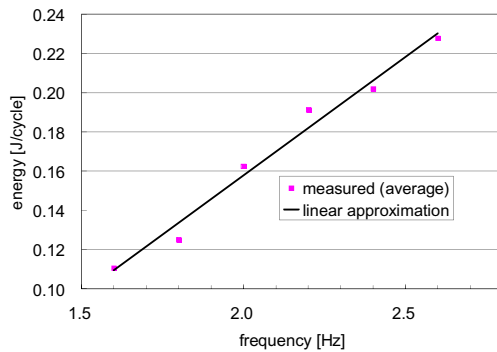
In the subsection 3.2, we described a method of phase tuning to control the quantity of energy transfer. That requires desired quantity of energy transfer for successful rope turning. The desired value should vary according to the frequency of the rope turning, because the quantity of energy dissipation in the rope depends on the frequency. We determine the desired value using teaching by human demonstration.

Teaching of desired energy transfer is carried out as follows:

- The manipulator turns the rope at a constant frequency. The human partner also turns the rope cooperatively so that the rope turns smoothly.
- We measure the quantity of energy transfer between the manipulator and the rope over each cycle.



(a) Measured Energy Transfer at 2.4Hz



(b) Relationship between Frequency and Energy Transfer

**Fig. 5 Frequency-Energy Relationship from Human Demonstration**

Fig. 5(a) shows a result of teaching at 2.4 [Hz]. By repeating the above sequence for various frequencies, we get the relationship between the frequency of the rope and energy transfer by the manipulator over one cycle as Fig. 5(b). Each plotted point means an average of measured data at each frequency. The results show that the quantity of energy transfer increases linearly with the frequency of the rope. We therefore determine the desired quantity of energy transfer by least-squares method as follows:

$$E_{\text{desirec}} = 12f_2 - 08 \quad (4.1)$$

where  $f_2 = \frac{\pi}{T}$  is the frequency of the rope, which can be estimated by LPLL.

#### 4.3 Design of Control Parameters

For cooperative rope turning, we set specifications of LPLL for frequency synchronization as follows:

$$\begin{cases} \omega_0 = 2 [\text{Hz}] = 4\pi [\text{rad/s}] \\ \Delta\omega_L = \frac{5}{6} [\text{Hz}] = \frac{5}{3}\pi [\text{rad/s}] \\ K_0 = 314 \\ K_d = 1 \\ \zeta = 1 \\ T = 0.0023 [\text{s}] \end{cases} \quad (4.2)$$

where  $\Delta\omega_L$  is lock range of LPLL and  $\zeta$  is the damping factor of the LPLL. Based on the design methodology described in [11], we can calculate the following intermediate parameters from the specifications:

$$\begin{aligned} \omega_n &= \frac{\Delta\omega_L}{2\zeta} = 2.62 [\text{rad/s}] \\ \tau_1 &= \frac{K_0 K_d}{\omega_n^2} = 45.9 [\text{s}] \\ \tau_2 &= \frac{2\zeta}{\omega_n} = 0.764 [\text{s}] \end{aligned}$$

where  $\omega_n$  is the natural frequency of the LPLL,  $\tau_1$  and  $\tau_2$  are time constants of low pass filters. Then we obtain the filter coefficients as follows:

$$\begin{cases} a_1 = -1 \\ b_0 = \frac{T}{2\tau_1} \left[ 1 + \frac{1}{\tan(T/\tau_2)} \right] = 0.00835 \\ b_1 = \frac{T}{2\tau_1} \left[ 1 - \frac{1}{\tan(T/\tau_2)} \right] = -0.00830 \end{cases} \quad (4.3)$$

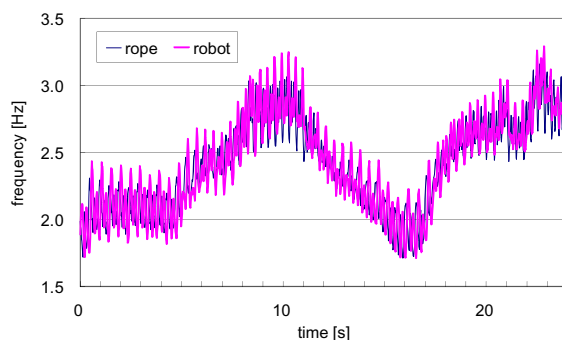
where we adopt a digital filter based on active PI filter. Thus all the parameters of LPLL are determined.

In regard to phase tuning, we set the feedback gain  $K_p = 0.0[\text{rad/J}]$  by trial and error.

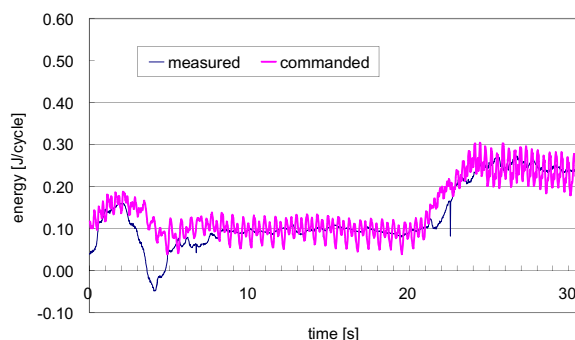
#### 4.4 Cooperative Rope Turning

Here we present the experimental results of cooperative rope turning by a man and a manipulator.

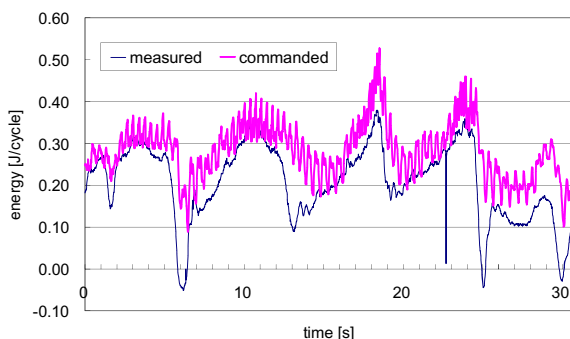
By our approach based on rhythm entrainment, the manipulator achieved successful rope turning. Fig. 6



**Fig. 6 Frequency Synchronization**



(a) Successful Case



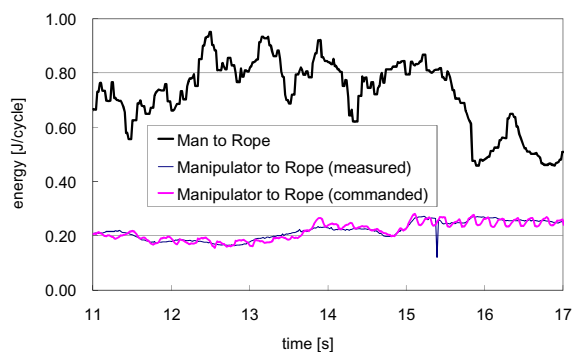
(b) Unsuccessful Case

**Fig. 7 Energy Transfer from Manipulator to Rope**

shows a result of frequency synchronization. The frequency of the rope in the graph was estimated by LPLL. In this case, the human partner purposely changed the frequency of rope turning as “fast-slow-fast,” then the manipulator could follow his motion quickly and stably. In successful cases, the human partner feels comfortable, because the manipulator supports cooperative rope turning properly, and besides, he can take the initiative of rope turning. Thus we consider that mechanical cooperation between the man and the manipulator was realized.

Fig. 7(a) shows a time series of energy transfer between the manipulator and the rope at every cycle in another successful case. The manipulator could transfer energy to the rope that is almost equal to desired values. Fig. 7(b) also shows a time series of energy transfer in other case, where we intentionally inflate the commanded value for energy transfer by 50%. By the inflation, we intended to test the behavior of the manipulator when the commanded energy transfer is different from what calculated by human demonstration. In this case, the commanded value was improper, so the manipulator could not carry out the commanded energy transfer, shown as Fig. 7(b). Therefore the motion of the manipulator could not synchronize with that of its human partner and the rope slackened periodically. The result indicates that the decreasing mechanical interaction between subsystems is essential to cooperation.

We compared the quantities of energy transfer by both the manipulator and the man to evaluate the quality of achieved cooperation. Fig. 8 shows the energy transfer by the manipulator and by the man to the rope in successful cooperation. The quantity of energy transfer from the man to the rope is about 4 times as that from the manipulator; the human partner is working harder in the sense of energy transfer. That is, we realized stable cooperation, but it is not equal one. In cooperative rope turning, the load of energy transfer and the initiative of rope turning are inseparable. Thus the evaluation of the



**Fig. 8 Comparison of Energy Transfer**

quality of cooperation should be multilateral.

## 5 Conclusion

We realized cooperative rope turning between a man and a manipulator based on rhythm entrainment. The entrainment consists of frequency synchronization by LPLL and phase tuning based on the control of energy transfer. Control parameters are easily determined by established design methodology of PLL and teaching from human demonstration. Stable cooperation is achieved based on a very simple model, which suggests that our approach is effective in general for human-robot mechanical cooperation. Application of the approach to other cooperative tasks is our future work.

At this stage, the achieved cooperation between the man and the manipulator is not equal; the man has to take more load of energy transfer, but takes the initiative of rope turning in return. To determine balanced point between such a conflicting demand for cooperation is a problem to be solved.

## Acknowledgement

This research was partly supported by Electro-Mechanic Technology Advancing Foundation.

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