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Human-Robot Cooperative Manipulation with Motion Estimation

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Abstract

In this paper, a control method of robots for human-robot cooperative manipulation is investigated. We propose estimating human motion using the minimum jerk model for smooth cooperation. Using nonlinear least-squares method, we identify two parameters of the minimum-jerk model in real-time. The estimated position of the human hand is used to determine the desired position of the end-effector of the manipulator in virtual compliance control.

The effectiveness of the proposed method is verified by experimentation with an industrial 6-degree-of-freedom manipulator. Energy transfer in cooperative manipulation is studied for quantitative evaluation of achieved cooperation from the viewpoint of adaptation theory.

1 Introduction

Human-robot cooperation is one of the key technologies to broaden the application field of robots. The combination of human intelligence and robot power will be effective in more complicated situations where robots used to be inapplicable. Therefore, in recent years, many researchers deal with a typical human-robot cooperation — cooperative manipulation ([1]-[4]).

Rahman et al. proposed incorporating human characteristics in the control system of robots to make them human-friendly in cooperative manipulation [5]. They implemented human-like impedance characteristics on their one-degree-of-freedom robot and achieved “good” characteristics for cooperation. In their method, however, we must embed different characteristics of time-variance of impedance for each of desired trajectories of the object.

In this paper, we investigate a control method of robots for human-robot cooperative manipulation (Fig. 1) with human-friendly characteristics that are effective for not only a specific trajectory but also various trajectories of the operators. Rahman et al. reported that the trajectory of the object in human-robot cooperation should conform to Flash and Hogan’s minimum jerk model [5][6]. Therefore we propose a robot control method by estimating the motion of its human partner with the minimum jerk model in real-time. The estimated position of the human hand is treated as the desired position of virtual compliance control [7]. The motion estimation enables robots to follow their human partners compliantly and actively. We implement our method on a conventional 6-degree-of-freedom manipulator, and experiment on human-robot cooperative manipulation of a rubber pipe. The experimental results are evaluated quantitatively from the viewpoint of “unnecessary interaction” of adaptation theory [8][9].

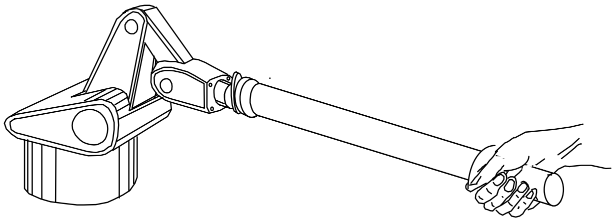


Fig. 1 Human-Robot Cooperative Manipulation

2 Virtual Compliance Control for Cooperative Manipulation

Virtual compliance control is a method to implement impedance characteristics on conventional position-controlled manipulators using force sensors [7]. In virtual compliance control, the motion of the robot is determined by the following equation:

$$\boldsymbol{M}\ddot{\boldsymbol{x}} = \boldsymbol{f} - \boldsymbol{D}\dot{\boldsymbol{x}} - \boldsymbol{K}(\boldsymbol{x} - \hat{\boldsymbol{x}})\,, \qquad (2.1)$$

where $\boldsymbol{M}$, $\boldsymbol{D}$, and $\boldsymbol{K}$ is the virtual mass, damper, and stiffness matrix, respectively; $\boldsymbol{x}$ and $\hat{\boldsymbol{x}}$ is the actual and desired position of the robot; $\boldsymbol{f}$ is the external force applied to the robot. The virtual impedance characteristics are freely programmable. In discrete-time systems, eq. (2.1) can be rewritten as:

$$\boldsymbol{M}\frac{(\boldsymbol{x}_{n+1} - \boldsymbol{x}_n) - (\boldsymbol{x}_n - \boldsymbol{x}_{n-1})}{(\Delta t)^2} = \boldsymbol{f} - \boldsymbol{D}\frac{\boldsymbol{x}_n - \boldsymbol{x}_{n-1}}{\Delta t} - \boldsymbol{K}(\boldsymbol{x}_n - \hat{\boldsymbol{x}}_n)\,, \qquad (2.2)$$

where $\boldsymbol{x}_n$ and $\hat{\boldsymbol{x}}_n$ is the actual and desired position of the robot at the n-th sample, and Δt is the sampling time. $\boldsymbol{x}_{n+1}$ is determined by eq. (2.2) using the force sensor attached to the manipulator. If $\boldsymbol{K} = \boldsymbol{O}$ (or equivalently, $\hat{\boldsymbol{x}}_n = \boldsymbol{x}_n$), the robot can compliantly follow the motion of its human partner ("direct teaching mode" in [7]). In the next section, however, we actively control the robot by changing $\hat{\boldsymbol{x}}_n$ in real-time according to the estimation of the human motion.

3 Estimation of Human Motion

In the minimum jerk model [6], human arm movements can be formulated as trajectories that minimize the following objective function:

$$J = \int_0^{t_f} \left\| \dddot{\boldsymbol{x}} \right\|^2 dt\,, \qquad (3.1)$$

where t_f is the duration of the movement. Assuming $\dot{\boldsymbol{x}} = \boldsymbol{0}$ and $\ddot{\boldsymbol{x}} = \boldsymbol{0}$ when $t = 0$ and $t = t_f$, we have

$$\begin{aligned}\boldsymbol{x} &= \boldsymbol{f}(t;\, t_f, \boldsymbol{x}_f) \\ &= \boldsymbol{x}_0 + (15\tau^4 - 6\tau^5 - 10\tau^3)(\boldsymbol{x}_0 - \boldsymbol{x}_f)\,, \qquad (3.2)\end{aligned}$$

where $\boldsymbol{x}_0$ and $\boldsymbol{x}_f$ is the initial and goal position of the arm movement respectively, and $\tau = t/t_f$ $(0 \le \tau \le 1)$. Fig. 2 illustrates a trajectory represented by eq. (3.2).

Because the minimum jerk model is also applicable to human-robot cooperative tasks [5], we estimate the human motion in cooperative manipulation by using this model in real-time. We determine unknowns in eq. (3.2), t_f and $\boldsymbol{x}_f$, by a weighted least-squares method so that the following function is minimized:

$$\sum_{i=0}^{n}\left(\frac{\left\| \boldsymbol{x}_i - \boldsymbol{f}(i\Delta t; t_f, \boldsymbol{x}_f) \right\|}{\alpha^{n-i}}\right)^2\,, \qquad (3.3)$$

where α is a forgetting factor ($0 < \alpha < 1$). We adopt Levemberg-Marquard method [10] for the nonlinear least-squares estimation to identify t_f and $\boldsymbol{x}_f$. The desired trajectory for virtual compliance control is

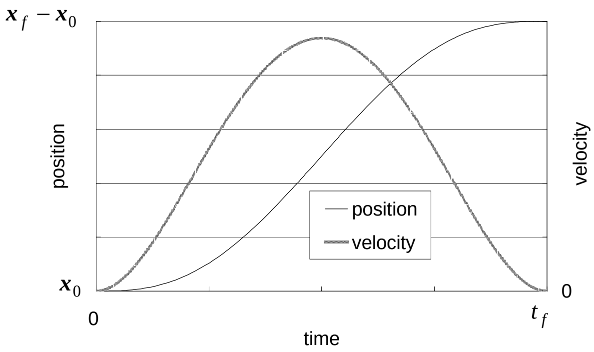


Fig. 2 Trajectory by Minimum Jerk Model

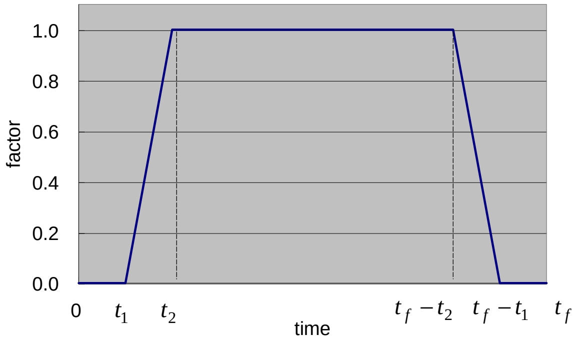


Fig. 3 Weight Coefficient for Virtual Stiffness

given by $\hat{\boldsymbol{x}} = \boldsymbol{f}(t; t_f, \boldsymbol{x}_f)$. This estimation enables the robot to follow the motion of its human partner more actively than “direct teaching mode.” At the first stage of the cooperation, however, the estimation from few data may cause unstable motion of the robot. Also at the last stage, the desired position from motion estimation may prevent the positioning of the object as the human operator intends. Thus we set the stiffness matrix $\boldsymbol{K}$ as follows (see Fig. 3):

$$\boldsymbol{K} = a\boldsymbol{K}_0, \tag{3.4}$$

$$\text{where} \quad a = \begin{cases} 0 & (0 \le t \le t_1) \\ \dfrac{t - t_1}{t_2 - t_1} & (t_1 \le t \le t_2) \\ 1 & (t_2 \le t \le t_f - t_2) \\ \dfrac{t_f - t_1 - t}{t_2 - t_1} & (t_f - t_2 \le t \le t_f - t_1) \\ 0 & (t_f - t_1 \le t \le t_f) \end{cases}.$$

$\boldsymbol{K}_0$, t_1 and t_2 are constants.

4 Experiment of Cooperative Manipulation

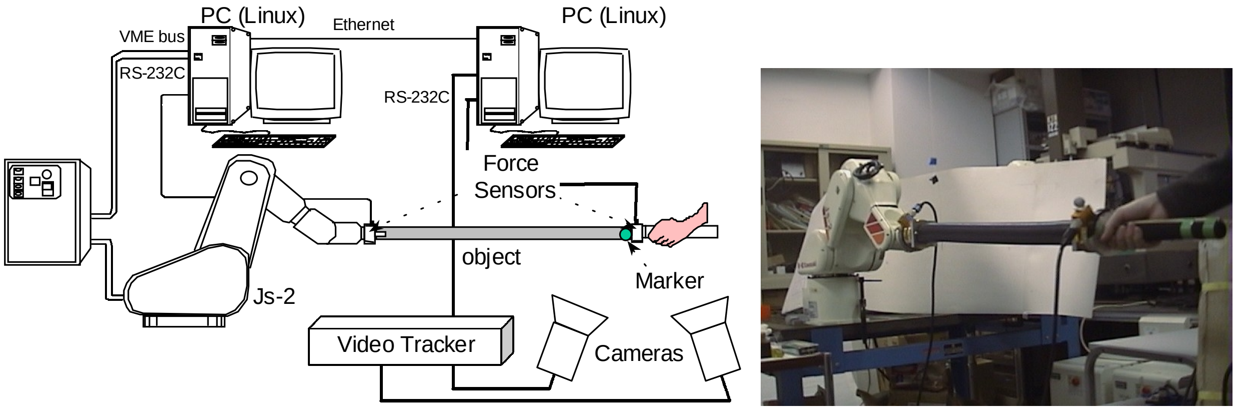
4.1 Experimental Setup

Our experimental setup for human-robot cooperative manipulation is illustrated in Fig. 4. As a handled object, we use a 500 [mm] rubber pipe of 1.6 [kg]. A human operator grasps one end of the object, and the robot grasps the other end. Both support the weight of the object jointly. We use a 6-degree-of-freedom manipulator “Js-2” (by Kawasaki Heavy Industry), which is position-controlled at 16 [ms] intervals. A force sensor is located at the endpoint of the manipulator and samples 6-axis force/torque data at 2.3 [ms] intervals. A Linux PC with a Classic Pentium controls the manipulator and the force sensor.

To analyze force and energy transfer by human operators, 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, “VideoTracker G280” by OKK Inc. The system can measure 3D coordinates of reflecting markers attached to the human-side end of the object at 60 [Hz] to a precision of about 1.0 [mm] by the direct linear transformation (DLT) method [11]. Using these apparatus, another Linux PC with a Pentium II collects force and motion data of the human operators for analysis of the experimental results. Note that the robot is controlled without the human force/motion data.

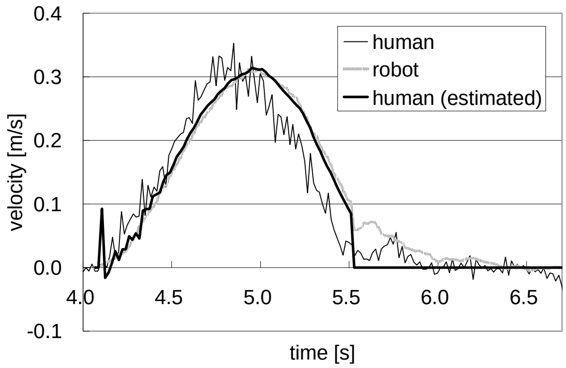
4.2 Cooperative Manipulation

We have made experiments of human-robot cooperative manipulation. For simplicity, the cooperative task in the experiments was limited to horizontal one-dimensional transportation of the object. The human operators carried the object from the initial position to the goal position at arbitrary

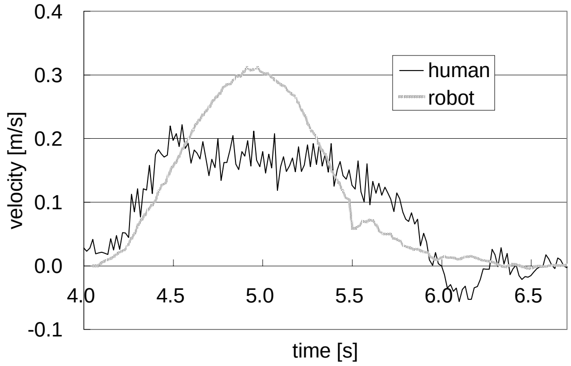


(a) Schematic View of Experimental Setup (b) A Scene of Cooperative Manipulation

Fig. 4 Experimental Setup for Cooperative Manipulation



(a) with estimation



(b) without estimation

Fig. 5 Motion in Cooperative Manipulation

speed in cooperation with the manipulator. The manipulator was controlled with motion estimation (our proposed method) or without motion estimation ($\boldsymbol{K} = \boldsymbol{O}$, "direct teaching mode") for comparison. We set the impedance parameters as follows:

$$\boldsymbol{M} = \begin{bmatrix} 1.79 & 0 & 0 \\ 0 & 1.79 & 0 \\ 0 & 0 & 1.79 \end{bmatrix} [\text{kg}] \tag{4.1}$$

$$\boldsymbol{D} = \begin{bmatrix} 48.0 & 0 & 0 \\ 0 & 48.0 & 0 \\ 0 & 0 & 48.0 \end{bmatrix} [\text{Ns/m}] \tag{4.2}$$

$$\boldsymbol{K}_0 = \begin{bmatrix} 800 & 0 & 0 \\ 0 & 800 & 0 \\ 0 & 0 & 800 \end{bmatrix} [\text{N/m}]. \tag{4.3}$$

Other additional parameters were:

$$\alpha = 0.91, \ t_1 = 0.1 t_f, \ t_2 = 0.2 t_f, \ \Delta t = 16[\text{ms}].$$

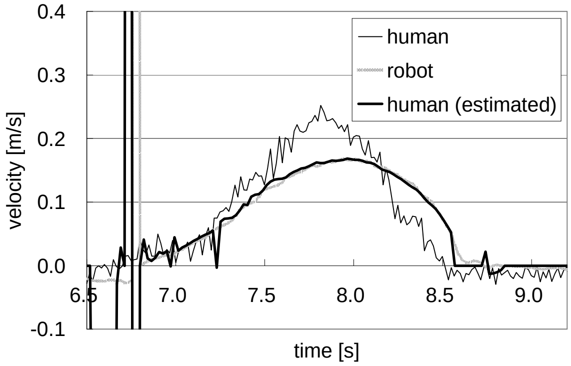


Fig. 6 Slower Manipulation with Estimation

Fig. 5 shows typical experimental results of the motion of a human and the manipulator for about 0.25 [m] horizontal translation. With motion estimation, the manipulator actively followed the motion of its partner, therefore the velocity profiles of both the human and the robot are similar to a trajectory by the minimum jerk model. In this case, the human operator could manipulate the object almost as he intended. The delay of the robot motion against the operator was mainly caused by the elasticity of the rubber object. On the other hand, without motion estimation, the velocity of the human motion hit the ceiling at the early stage because of the poor response of the robot. In this case, the human operator could not manipulate the object just as he intended, and felt "heavy" for manipulation.

Fig. 6 shows a result when a human operator tried to manipulate the object at slower speed than the case of Fig. 5 (a). The velocity profiles of the human and the robot are not very much alike because of the elasticity of the object. However, the trajectory of the human hand is similar to that by the minimum jerk model, which means that the operator could move his hand almost as he intended.

Human operators reported that they felt "light" for cooperative manipulation with motion estimation in comparison with conventional "direct teaching mode." We consider that our proposed method gives robots human-friendly characteristics for manipulation.

5 Study on Energy Transfer in Cooperative Manipulation

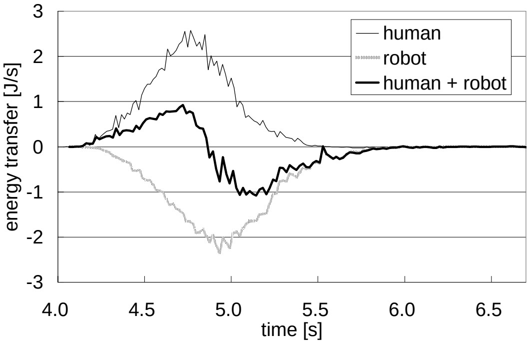
In the context of pattern generation of decentralized autonomous systems, Ito et al. defined adaptation of biological systems as "a process of decreasing subsystem interaction" [8][9]. In their view, disharmony between subsystems finds expression in unnecessary interaction; therefore the subsystems modify their behavior to decrease interaction locally in adaptation process. Applying Ito's view to robotic cooperative tasks, it should be important for cooperation to decrease unnecessary mechanical interaction between subsystems, such as energy transfer between cooperating partners. Thus we can use the quantity of energy transfer in cooperative tasks as a quantitative measure of the quality of achieved cooperation.

Fig. 7 shows the energy transfer from the human operator to the object (E_{h}) and from the robot to the object (E_{r}) in the cases of Fig. 5. The sum of both ("human + robot", $E_{\mathrm{h}} + E_{\mathrm{r}}$) means the net energy spent to accelerate/decelerate the object. In the first half of manipulation (acceleration phase), the energy flows from the human into the object and the robot (Fig. 8). In the deceleration phase, the energy from the human and the object flows into the robot. In such manipulation tasks, total unnecessary energy transfer, $E_{\mathrm{unnecessary}}$, which is the quantity of "unnecessary interaction," is the area of stippled region in Fig. 9. $E_{\mathrm{unnecessary}}$ can be calculated as follows:

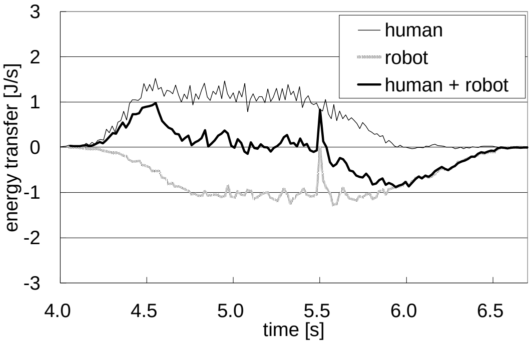
$$E_{\mathrm{unnecessary}} = \frac{1}{2}\int (|E_{\mathrm{h}} - E_{\mathrm{r}}| - |E_{\mathrm{h}} + E_{\mathrm{r}}|)dt \quad (5.1)$$

Note that the areas of stippled region and crosshatched region in Fig. 9 are equal.

The averages of $E_{\mathrm{unnecessary}}$ for five trials by three human operators are shown in Fig. 10. The difference among operators mainly results from the difference of manipulation speed for each. The estimation of human motion reduces unnecessary energy transfer, which implies that the robot could adapt itself to the human partner better than that without motion estimation.



(a) with estimation



(b) without estimation

Fig. 7 Energy Transfer in Cooperative Manipulation

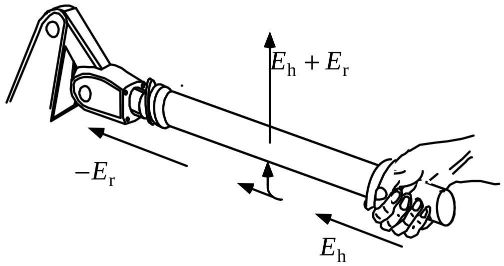


Fig. 8 Energy Transfer in Acceleration

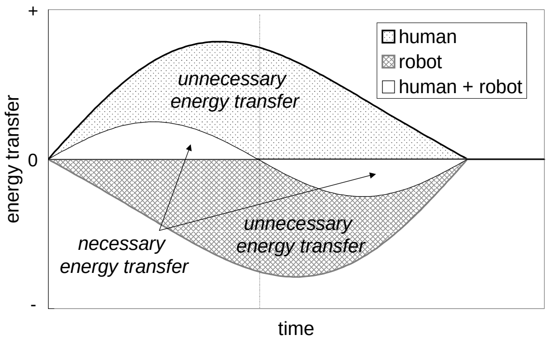


Fig. 9 Schematic View of Energy Transfer by Human and Robot

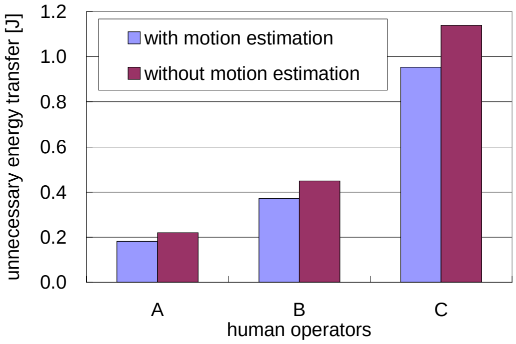


Fig. 10 Average Energy Transfer with/without Motion Estimation

The authors analyzed the energy transfer in human-robot cooperative rope turning in [12]. This paper gives another example of energy transfer in human-robot cooperation. These results suggest the effectiveness of adaptation theory for robotic cooperative tasks.

6 Conclusion

In this paper, we proposed a method of virtual compliance control with real-time estimation of the human motion for human-robot cooperative manipulation. To incorporate human characteristics, we adopted the minimum jerk model for the estimation. The method was implemented on a conventional 6-degree-of-freedom manipulator and experimental results on horizontal manipulation showed the improvement of human feeling of manipulation. The experimental results were quantitatively evaluated from the viewpoint of the energy transfer during the task.

Future work should address the estimation of more complex motion in human-robot cooperative manipulation.

Acknowledgments

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