Development of a manipulator with an opposed-placement-type ER clutch contributing to collision force reduction

A Inoue, N Kanno, M Yoshikawa and T Nakamura

Chuo University, Biomechatronics Laboratory, 1-13-27 Kasuga, Bunkyo-ku, Tokyo, 112-8551, Japan

E-mail: nakamura@mech.chuo-u.ac.jp

Abstract. In recent years, human and robots have begun to work together in the fields of medical treatment and welfare. In such environments, robots must be designed to operate safely; thus, reducing collision force when collision is occurred with their human colleagues is essential. In this study, a manipulator with opposed-placement-type electrorheological (ER) clutches is designed to reduce the collision force. The main feature of the manipulator is a structure that sandwiches the link between two ER clutches and equips the link with a pneumatic cushion. The input shaft of each clutch is rotated in the opposite direction via a bevel gear and a spur gear from an electric motor. Because the link can be reversed by switching the clutch, the manipulator can operate in high-speed reverse motion. Position control, reverse motion control and collision experiments were performed to test the effectiveness of the manipulator. The reverse motion control experiment revealed that the manipulator can reverse more rapidly than a conventional manipulator, which is only driven by a motor. From the collision control experiment, it was found that the manipulator can reduce the collision force more effectively than the conventional manipulator.

1. Introduction

Recently, humans and robots have begun to work together in the fields of medical treatment and welfare [1-3]. In such environments, robots must operate safely so as to avoid collisions or inadvertent contacts with their human colleagues. A manipulator with an electrorheological (ER) clutch and a pneumatic cushion sensor has been developed as a robot arm that satisfies this requirement [4, 5]. Because of its flexible joint, this manipulator can reduce collision and contact forces, but has proven difficult to control. To address this problem and further reduce the collision force, high-speed reverse motion control has been proposed [6].

In this study, we developed a manipulator that can be reversed at high speed. Figure 1 illustrates the manner in which the manipulator achieves the intended high-speed reversal motion. In stage 1, a collision occurs. A pneumatic cushion sensor detects the collision and pushes the colliding object. In stage 2, a reversal torque is instantaneously generated so that the impact force is reduced by an amount dependent on the reduction in pushing distance and contact time. In stage 3, the situation following operation of the reversal motion control is illustrated.

In this paper, we demonstrate the action of the developed manipulator with an opposed-placement-type ER clutch in terms of impact force reduction. The ability of the manipulator to reduce collision forces is tested in a series of collision experiments.

1 Corresponding author.
Figure 1. Schematic of idealized high-speed reverse motion control.

2. Manipulator with the opposed-placement-type ER clutch
The developed manipulator and its specifications are presented in Figure 2 and Table 1, respectively. This manipulator comprises two ER clutches, an electric motor and a pneumatic cushion.

Figure 2. Configuration of the developed manipulator.

Table 1. Specifications of the manipulator.

| Parameter                                      | Value       |
|-----------------------------------------------|-------------|
| Length of the link                            | 0.3 [m]     |
| Mass                                          | 0.2 [kg]    |
| Rotation angle                                | 215 [deg]   |
| Center of gravity position                    | 0.12 [m]    |
| Inertia (Link + output shafts of ER clutches) | 0.026 [kgm²]|
| Human pain tolerance                          | 13 [N]      |
| Contact position of the base of the link      | 0.2 [m]     |
| Initial pressure of the pneumatic cushion     | 5 [kPa]     |

2.1. Mechanism of the opposed-placement-type ER clutch
Figure 3 shows the mechanical design and the driving mechanism of the arm. The main feature of the manipulator is the structure that sandwiches the link between two clutches. With this structure in place, the input shaft of each clutch can rotate in the opposite direction via a bevel gear, a spur gear and a motor. The arm is attached to the output shafts of the ER clutches. High-speed reversal of the arm is achieved by switching to another input shaft that drives another ER clutch, not by reversing the motor. As a result of reversing the link by switching the clutch and ignoring the inertia of the motor and gear, the manipulator can reverse at high speed.
2.2. ER clutch

Figure 4 and Table 2 display the configuration and specifications of the ER clutches, respectively. Figures 5 and 6 show the dependence of the torque transmitted to the ER clutches on the applied electric field and the angular rotation speed of the input shaft. In these figures, the applied electric field is increased from 0 to 2.0 kV/mm in 0.5 kV/mm increments, while the rotation speed is increased from 5 to 20 r/min in 5r/min increments. It is seen that the transmitted torque increases by applied electric field. In addition, we note that torque does not depend on the rotation speed.

The clutch is made by ER Tech. Multiple disks are mounted on the input and output shafts. The ER fluid enclosed between these disks transmits the torque from the input to the output shaft. The transmitted torque can be increased by applying an electric field independent of temperature. In addition, the torque rapidly responds to the applied electric field. Therefore, this high-speed reverse motion shows promising future applicability. ER clutches 1 and 2 generate a maximum transmitted torque of about 12 Nm and 7 Nm, respectively, under an electric field of 2.0 kV/mm. The maximum transmitted torque of the ER clutches is decided by calculating the torque required to reverse the arm in advance. In this study, the maximum transmitted torque performances of the two ER clutches are designed to be different to enable a differential investigation of impact force reduction and reverse speed.

![Figure 4. Configuration of the ER clutch.](image-url)
### Table 2. Specifications of the ER clutch.

| Parameter                        | Value (ER clutch1) | Value (ER clutch 2) |
|----------------------------------|--------------------|---------------------|
| Maximum torque [Nm]              | 12                 | 7                   |
| Output shaft [mm]                | φ 20               | φ 15                |
| Input shaft [mm]                 | φ 25               | φ 20                |
| Diameter [mm]                    | 215                | 185                 |
| Weight [kg]                      | 8.2                | 6.1                 |
| Thickness [mm]                   | 56                 | 56                  |
| Outer disk diameter [mm]         | 170                | 140                 |
| Inner disk diameter [mm]         | 90                 | 70                  |
| Number of sheets of the disk     | 4                  | 4                   |
| Disk thickness [mm]              | 1                  | 1                   |

![Figure 5](image1.png)  
**Figure 5.** Relationship between the rotational speed and torque of the ER clutch (7 Nm) as a function of the electric field.

![Figure 6](image2.png)  
**Figure 6.** Relationship between the rotational speed and torque of the ER clutch (12 Nm) as a function of the electric field.

#### 2.3. Pneumatic cushion

Figure 7 illustrates the pneumatic cushion attached to the link of the developed manipulator. The cushion specifications are listed in Table 3. The pneumatic cushion reduces the collision force that is measured by internal pressure changes, which are detected by a pressure sensor.

![Figure 7](image3.png)  
**Figure 7.** Schematic of the pneumatic cushion

### Table 3. Specifications of the pneumatic cushion.

| Parameter       | Value       |
|-----------------|-------------|
| Outer diameter  | 100 [mm]    |
| Inner diameter  | 20 [mm]     |
| Length          | 140 [mm]    |
| Thickness       | 0.05 [mm]   |
| Material        | Polyurethane|
2.4 Experimental system

Figure 8 illustrates the control system of the manipulator. The manipulator is driven by an electric motor. The torque generated by the motor is transmitted by the ER clutches, which in turn powers the link. The control system consists of a MATLAB and Simulink interface with dSPACE. The angle of the input shaft is measured by counting the output pulses by the encoder interfaced to a PC, while that of the output shaft is measured by a potentiometer.

![Configuration of an experimental system](image)

**Figure 8.** Configuration of an experimental system.

3. Experiment

3.1. Position control experiment

The aim of the position control experiment is to test the positioning accuracy when a changing electric field is applied to the ER clutch.

The target angle of the arm is set to 180°, and the electric field applied to ER clutch1 is increased from 0.5 to 2.0 kV/mm in 0.5 kV/mm increments. The target angle command is executed in the first second following the start of the experiment.

The results of the experiment are plotted in Figure 9. This figure shows that precise angle control is possible under electric fields exceeding 0.5 kV/mm. Low electric fields are insufficient to overcome the friction and base viscosity of the clutches; hence, the arm is not moved at applied electric fields below 0.5 kV/mm. The curve is static for the first few seconds following the increase in the target angle because of the delay in transmitting the torque from the motor to the output shaft of the ER clutch.

![Results of the position control experiment](image)

**Figure 9.** Results of the position control experiment.
3.2. Reverse control experiment

To determine whether the developed manipulator can achieve the desired level of high-speed reverse motion control, a reverse motion experiment was conducted under three separate regimes.

Regime 1: The arm is reversed by switching the ER clutch.
Regime 2: The arm is reversed by controlling the motor, but with the manipulator attached to the ER clutch.
Regime 3: The arm is reversed by controlling the motor.

Figure 10 shows the experimental setup. First, the input shaft of each ER clutch is rotated by the motor, and the arm is rotated such that the electric field is only applied to ER clutch 1. Once the angle of the arm has reached 180°, reverse motion control is implemented. In the first regime, the applied electric field is switched to the other clutch when the arm angle reaches 180°. At this time, the rotational direction of the motor is not changed. In the second regime, the electric field is always applied to ER clutch 1, but the rotational direction of the motor is changed, and the arm is reversed once its angle reaches 180°. In the third case, as the arm angle reaches 180°, the rotational direction of the motor itself alters. In this regime, the manipulator without the ER clutch is used.

The results of the reverse motion control experiment are plotted in Figure 11. The black solid line, black dashed line and grey line show the responses under regime 1, 2 and 3, respectively. The vertical dashed line in the figure indicates the time at which the arm reaches 180°. Switching of clutches (regime 1) is seen to be the fastest means of achieving angular reversal (cf. regimes 2 and 3). From the figure, the overshoot of regimes 1, 2 and 3 is 1.3°, 5.7° and 6.8°, respectively. Under regime 2, the angle reaches a maximum of 185.7° and does not immediately decline thereafter (note the horizontal section of the curve). This phenomenon occurs because of the slip between the input and output shafts of ER clutch 1 as the motor is reversed. Consequently, the response of the system under regime 2 following reversal is slower than that under regime 3.

Figure 10. Left section shows the manipulator with the ER clutch used in experimental tests 1 and 2. However, under regime 2, ER clutch 2 is not used to reverse the arm. The right section shows the manipulator without the ER clutch tested in regime 3.
3.3. Collision experiment

To confirm whether the developed manipulator can effectively reduce the collision force, a collision experiment is conducted, the setup of which is shown in Figure 12.

First, the arm is rotated, causing the link to collide with the force sensor. Next, when the collision force surpasses the threshold (the human pain tolerance [7]), this link is reversed by each of the three methods described in 3.2. Table 1 summarizes the experimental conditions. The following experimental designs were implemented:

Regime 1: Motion is reversed by changing the ER clutch. The motor is rotated in a constant direction after collision.
Regime 2: Motion is reversed by controlling the motor. The manipulator used this test is fixed to an ER clutch.
Regime 3: Motion is reversed by controlling the motor. The manipulator used in this test is not attached to the ER clutch.
Regime 4: This test is non-reverse motion control. Only the force sensor is pushed. The manipulator is not attached to the ER clutch under this regime. The arm is directly driven by the motor.

The results of this experiment are plotted in Figure 13. From the figure, it is seen that reversing the motion by switching the clutch is the most effective at reducing the collision force (the contact time is reduced in regime 1 relative to the other tests). The reason of the wavy response (regime 4) results from jumping phenomenon of the bevel gear.

From the figure, the maximum impact forces under all regimes are seen to exceed the threshold (the human pain tolerance). This is because that we set the threshold to be equal to that of human pain tolerance without taking into account the dynamic characteristics of the ER clutches and the pneumatic cushion sensor. In future, the threshold will be decided on these dynamic characteristics.

Figure 11. Results of the reverse motion control experiment.

Figure 12. Schematic of the setup of the collision experiment.
8. Conclusion
In this study, we developed a manipulator with an opposed-placement-type ER clutch and tested its utility by position control, reverse motion control and collision experiments. From the position control experiment, the manipulator was found to exert precise positional control when an electric field exceeding 0.5 kV/mm is applied to the ER clutch. From the reverse motion control experiment, the developed manipulator was shown to reverse more rapidly than the conventional manipulator. The collision experiment revealed that the developed manipulator reduces collision forces more effectively than the conventional manipulator. However, the maximum collision force of the developed manipulator exceeds the threshold (the human pain tolerance) because of a time delay in the ER clutch and the pneumatic cushion sensor. In future studies, by accounting for the dynamic characteristics of the ER clutch and the pneumatic cushion sensor, we aim to reduce the maximum impact force to more desirable levels.

References
[1] Kawamura K and Iskarous M 1994 Trends in service robots for the disabled and the elderly Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems, 12–16 Sep 1994, Munich, Germany, pp. 529–51
[2] Woosub L, Junho C and Sungchul K 2009 Spring-clutch: A safe torque limiter based on a spring and CAM mechanism with the ability to reinitialize its position 2009 Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, 10–15 Oct. 2009
[3] Wand R-J and Han-Pang H 2010 An active-passive variable stiffness elastic actuator for safety robot systems Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems
[4] Boku K, Kusaka Y, Akamatsu Y and Nakamura T 2008 Development and control of three degrees of freedom soft manipulators which considered a collision with the environment that was able to include a human being J. Robot. Mechatron. 20 634–40 [Remark 9]
[5] Nakamura T, Akamatsu Y and Kusaka Y 2008 Development of soft manipulator with variable rheological joints and pneumatic sensor for collision with environment J. Robot. Mechatron. 20 634–40
[6] Yoshikawa M, Boku K and Nakamura T 2010 High speed switching control of 1 DOF manipulator using ER clutch Proc. 12th Int. Conf. Electrorheological Fluids and Magnetorheological Suspensions (ERMR2010)
[7] Yamada Y, Suito K, Ikeda H, Sugimoto N, Miura H and Nakamura H 1997 Evaluation of pain tolerance based on a biomechanical method for human-robot coexistence JSME 63 238–43