Development of 3 DOF manipulator using ER fluid clutches for reduction of collision force

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Development of 3 DOF Manipulator Using ER Fluid Clutches for Reduction of Collision Force

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Abstract. With robots and users more commonly sharing space such as in the fields of medicine and home automation, the possibility of a physical collision has increased, even though many robots use actuators with high-ratio gear trains to minimize the effects of impact. We developed a 3-DOF manipulator having a smart flexible joint using an ER fluid and a sensor-equipped pneumatic cushion. Results of position control and collision experiments using the manipulator demonstrated its effectiveness.

1. Introduction

Robots currently used in industrial applications are also expected to be used in homes and offices [1] alongside users. This means that robots coexist with users. Conventional safety strategies used for industrial robots cannot be applied to symbiotic robots working with users; therefore, safety strategies in coexisting space must be comprehensively studied. One critical consideration is user safety in an unexpected collision, not to mention damage to the robot. Approaches to collision avoidance contributing to user safety can be briefly summarized as follows: Collision can be suppressed by minimizing the robot’s effective arm mass with redundant degrees of freedom [2] or by specifying initial parameters, such as approach speed and force control gain. [3],[4] Sensor-guided control using optical, ultrasonic, and force/torque sensors on a robot’s wrists, for example, [5],[6] may pose problems with dead angles and disturbances, and thus, it is difficult to ensure optimum safety using these approaches. Many robot motors use mechanisms with a high reduction ratio and cannot sufficiently ensure safety in a collision. [7],[8],[9] Thus, mechanical flexibility must be added to the robot’s functions.

This study describes a manipulator we developed, whose joints and links have lower viscoelasticities than conventional models and whose rigid joints are controlled to a high degree of accuracy so that it can minimize collisions, and when it does collide with an object in the external environment (e.g., a human), the manipulator can ease the impact.

2. Soft Manipulator

We developed a three-link soft manipulator (Figure 1) that consists of three actuator-driven joints with a clutch on each joint, which uses an electrorheological (ER) fluid. [10],[11] The rotation axis is fixed by giving a viscous parameter to the ER clutch, and motor rotation is transmitted to the link. In this case, the motor’s rotation is transmitted to each pulley of joints by a timing belt.
A pneumatic cushion sensor on all links, [12] which provides a soft touch, operates while a pneumatic sensor encountering the object in the external environment exerts an appropriate initial pressure against the pneumatic cushion (Figure 2).

First, when the manipulator is driving, its behavior can achieve a highly accurate position control due to the provision of appropriate viscosity to the ER clutches. Next, when the manipulator collides with the external object (in this case, a human), the contact force can be decreased by reducing the flexibility of the buffer material and the viscous parameter of the joint, which minimizes the effect of contact and eases the collision force on the external object. Finally, it is the behavior of the manipulator that controls the reaction when the manipulator collides, evades the external object, and returns to trajectory after collision.

3. Pulley Layout
Each joint of the manipulator is driven by the timing belt. Figure 3 shows the pulley layout of each joint. Each joint layout consists of three layers. The direction of the belt is controlled by the idler pulley, which is not seen in Figure 3.

4. ER Clutch
A decentralized ER fluid is used for the clutch’s operational fluid. The viscosity of this fluid changes with the application of an electrical field. The fluid used in the clutch function in the joint has the following two advantages: [11],[13]

- Because fluid viscosity changes instantaneously, the joint responds more quickly to a collision than a conventional electromagnetic clutch.
- The clutch is lightweight and easily miniaturized because it uses only one electrode, suppressing the influence of manipulator inertia.

The torque required for the ER clutches must be calculated. Because the torque of ER clutches must be considered in the manipulator’s function, a value that compensates for the torque of each joint by dynamics is preferable. Figure 4 shows a schematic diagram of the ER clutch in this study. As shown in this figure, the sheets in the disk of the ER clutch were assumed to be composed of four multiple-layer structures. Therefore, because the electrode’s surface area was increased, miniaturization and high torque output could be achieved. Moreover, both the minus and plus electrodes are integrated within a signal housing installed directly along the I/O axis. In addition, the use of a cover diminishes the chance of an electric shock caused by the high voltage applied to the ER fluid. Figure 5 shows the relationship between torque and the electric field. This figure shows that torque increases when the applied electric field increases. Table 1 shows the specifications of the ER clutch in this study.

5. Pneumatic Cushion Sensor
The pneumatic cushion sensor uses the compressibility (elasticity) of internal air in a midair cylinder device as a buffer. In addition, by installing a pressure sensor in the air ingate of the buffer material
and measuring pressure changes, the pneumatic cushion is used as a sensor that has contact detection capability over a wide range.

It is necessary that the material of the pneumatic cushion has a low degree of elasticity and plasticity, because the buffer material used in this study may also function as a sensor. Thus, this study focuses on a polyurethane pneumatic cushion because of its strong tensile strength.

A shape that would cover the link of the manipulator was designed. Figure 6 shows a schematic diagram of the pneumatic cushion sensor (for the third link). There is a hole for the air enclosing the pneumatic cushion where a tube can be installed.

Figure 7 shows the relationship between the pressure and contact force, when the initial pressure is changed. This figure shows that irrespective of initial pressure values, the curves of the contact force vs. pressure are almost parallel. In addition, the range of detection of the contact force is wide when the initial pressure is higher. Therefore, the pneumatic cushion sensor can trade off the sensor effect and the buffer effect. Table 2 shows the specifications of the pneumatic cushion sensor developed in this study.

6. Experimental Results and Discussion

6.1. Experimental System
In experiments, the angle of each link is measured using a potentiometer (Figure 1). Maximum impact exerted on the link is detected by the pneumatic cushion (force sensor) in each link. The motor and ER clutch are controlled by a PC based on measured data. Human pain tolerance is the limiting value of the mechanical stimulation that causes pain in a human subject [14]. If this is exceeded, each joint is made flexible by ceasing to apply the ER clutch’s electrical field.

6.2. Position Control Experiment
We studied the positioning control of the manipulator by comparing when the ER clutch is and is not installed in the arm.

Figure 8 show the experimental results for the third joint, comparing cases with and without the ER clutch, in which the target angle ranges from 0° to 60°. When the angle is detected by the potentiometer, feedback control will be applied. When the ER clutch is installed (soft manipulator),

![Figure 4. Configuration of the ER clutch](image)

![Figure 5. Characteristics of the ER clutch](image)

<table>
<thead>
<tr>
<th>Table 1. Specification of the ER clutch</th>
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<tbody>
<tr>
<td>Joint number</td>
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<tr>
<td>Torque [Nm]</td>
</tr>
<tr>
<td>Diameter [mm]</td>
</tr>
<tr>
<td>Weight [kg]</td>
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<tr>
<td>Outside diameter of the disk [mm]</td>
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<tr>
<td>Inside diameter of the disk [mm]</td>
</tr>
<tr>
<td>Number of sheets of the disk [disk]</td>
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<td>Thickness of disk [mm]</td>
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the electric field is applied at 0.0 kV/mm and 3.0 kV/mm, and when the ER clutch is not installed (direct gear drive manipulator), the joint is driven directly by the motor. From this figure, the manipulator can guide the arm to an exact position when an electric field of 3.0 kV/mm is applied to the ER clutch. However, it can be inferred that the raising of the arm is delayed when an electric field of 0.0 kV/mm is applied to ER clutch compared to the case direct gear drive manipulator, and the joint does not reach the target angle. The joint cannot follow the rotation, because the inertial torque of the motor is larger than the retained torque of the ER clutch in this case. The experimental results for the first joint and the second joint is the same as the results for the third joint.

6.3. Collision Experiment
We studied four conditions related to collisions between the manipulator and something in its external environment when (1) the buffer element was not installed (direct gear drive), (2) only the ER clutch was installed, (3) only the pneumatic cushion was installed, and (4) both the ER clutch and the pneumatic cushion were installed (soft manipulator). Manipulator’s first joint drives at 10 rpm on the experiment. At the end point of the third link, the manipulator collides with an object in the outside environment that consists of a force sensor. Figure 9 shows the experimental results for the collision force.

In this figure, when the direct gear drive manipulator collides, the maximum impact force is generated and the contact force keeps generating after the collision. When the pneumatic cushion sensor was installed, the maximum impact force decreased compared with the direct gear drive, but the contact force remained. When the ER clutch was installed, the maximum impact force decreased. Moreover, the contact force could decrease to zero because when the third link collided with the external object, it never contacted the external object again by making the joint flexible after the collision. When the soft manipulator is installed in both the pneumatic cushion sensor and the ER clutch, the maximum impact force decreased most, and the contact force could decrease to zero.

7. Conclusion
This study describes a soft manipulator we have developed that ensures user safety in collisions between robots and an external object (e.g., humans), using a smart flexible joint composed of an ER fluid and a pneumatic cushion. We came to the following conclusions:
It was shown that the pneumatic cushion sensor could enable the manipulator to detect a collision with the external object and has sufficient buffer ability to cushion the maximum impact force.

To decrease external contact, we installed a clutch using an ER fluid on the manipulator’s joint. Control was sufficient in a positioning control experiment to confirm the effectiveness of the manipulator’s functionality. The collision experiment confirmed a decrease in contact impact.

In future research, we will examine the collision simulation of the manipulator and manipulator’s behavior after collision. Also, collision patterns will be compared to the soft manipulator and this simulation.

References


Figure 8. Step responses of position control for the third joint

Figure 9. Collision experiment of the soft manipulator