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Spring-Clutch: A Safe Torque Limiter Based on a Spring and CAM Mechanism with the Ability to Reinitialize its Position

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***Abstract*—Service robots are anticipated to be used in unstructured areas such as homes, hospitals, and public areas in the near future. However, safety issues need to be addressed before this can occur. In particular, robot manipulators that handle objects by physical contact run the risk of colliding with people or objects. Thus, it is important to prevent collisions that could injure people and damage robot manipulators. In this study, a safe joint mechanism is developed to ensure the safe use of a manipulator. This mechanism, termed 'Spring-Clutch,' is a simple passive mechanism that consists of a coil spring and a CAM mechanism. When a torque is applied that is less than a threshold value, Spring-Clutch functions as a rigid joint between the input and the output. However, when an applied torque exceeds the threshold, angular displacement occurs between the input and output to reduce the collision force. If the applied torque is removed, Spring-Clutch immediately returns to its nominal position without the need for additional operations. This paper describes the design principles and performance of Spring-Clutch, and discusses the possibility of its practical use as a joint mechanism for safe manipulation.**

I. INTRODUCTION

Robots, which have traditionally been used in factories, are increasingly being introduced to public areas. Similarly, the duties of robots are no longer restricted to simple manufacturing operations, but increasingly involve high-level service tasks that enhance the well-being of people. The ability to manipulate objects is very important for service robots. However, in the environments in which robot manipulators operate, there is a high possibility that a part of the robot manipulator will collide with a person or an object, causing injury to people and/or damage to the manipulator. For this reason, various methods for preventing collisions are currently being investigated to ensure safe manipulation. Previous studies in this regard can be classified into two broad categories. The first is active control methods that involve installing various sensors on robot manipulators and developing motion control algorithms based on feedback from the attached sensors to detect imminent collisions [1–4]. However, active control has several disadvantages, including the high cost and low reliability of the control system and limited absorption of the initial collision force [5]. The second category uses passive mechanisms to achieve safe manipulation. In this case, the collision force is absorbed by a passive mechanism without an additional active control method. The advantages of this approach over active control systems include the lower cost of the passive control system and its higher reliability. For these reasons, passive control methods are considered to be more suitable for general service robots [6].

Two approaches have been adopted for achieving safety through passive compliance: controlling the joint stiffness and fixing the joint stiffness to a predetermined value. Examples of the first method include an adjustable joint stiffness mechanism that employs a leaf spring [7] and a variable stiffness joint with a nonlinear spring mechanism consisting of two motors and a timing belt [8]. In a previous study, we designed a variable stiffness unit (VSU) that uses a magnetic mechanism [9]. However, an additional mechanism is required to change the stiffness by online, thereby increasing the volume, weight, and complexity of the structure. An example of a system with a fixed joint stiffness is a passive mechanism having a four-bar linkage mechanism [10].

In the present study, we developed a compact, lightweight, practical, and safe joint mechanism. To meet the above design requirements, the fixed joint stiffness method was selected. The proposed mechanism is called 'Spring-Clutch,' and it consists of coil springs, a simple CAM mechanism, and a small number of mechanical parts. It functions as a rigid joint when an external torque is applied that is less than the yield torque. When the applied torque exceeds the yield torque, however, Spring-Clutch rotates like a revolute joint, causing the joint to deflect. When the applied torque is removed, Spring-Clutch reinitializes itself.

The remainder of this paper is organized as follows. Section II describes the basic requirements for a safe joint mechanism and the design principles and operation of the proposed Spring-Clutch. Section III describes the mechanism developed for Spring-Clutch, while section IV presents the experimental results and performance of Spring-Clutch. Finally, concluding remarks and further work are presented in section V.

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II. Design and working principles of Spring-Clutch

A. Requirements of Spring-Clutch as a Safe Joint Mechanism

The safe joint mechanism developed in this study is designed to be used on a robot manipulator. In other words, Spring-Clutch needs to satisfy the specifications for a manipulator. To ensure efficient and accurate operation, manipulation requires highly accurate position control. This means that the safe joint mechanism, to be installed on a service robot manipulator, should not be deflected by various external joint torques generated by the payload or the posture of the manipulator. However, when the torque at a joint exceeds an acceptable value as the result of an unexpected collision, Spring-Clutch needs to decouple the dynamics of the joint from the rest of the manipulator. It is also desirable that the deflected joint returns to its nominal position when the external torque causing the deflection is removed. Thus, Spring-Clutch was decided to have the following specifications:

1) It operates as a rigid joint when the external torque is below the yield torque.
2) It operates as a revolute joint when the external torque exceeds the yield torque.
3) It initializes itself when the external torque is removed.

Spring-Clutch, which is a safe joint mechanism that satisfies the above three requirements, is presented in the next section.

B. Design and Operating Principles of Spring-Clutch

Figure 1 shows the basic concept of Spring-Clutch. The spring in Fig. 1 is compressed and the ball bearing, which is pushed by the compressed spring, contacts the plane at an angle α. The relationship between the forces in Fig. 1 can be expressed by

$$F_{spring} = Ke \ , \quad (1)$$

$$F_a = F \sin\alpha \ , \quad (2)$$

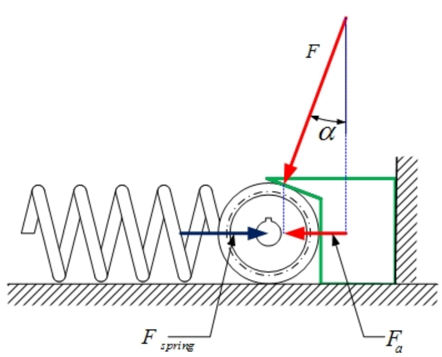

Fig. 1. Schematic of Spring-Clutch.

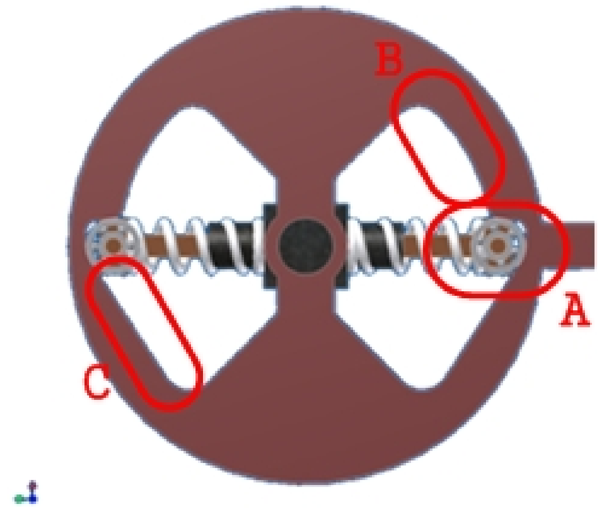

Fig. 2. Design of Spring-Clutch

where K is the spring constant, e is the compressed length, α is the angle of the plane, and F is the external force. The motion of the bearing is then defined as follows:

1) $F_{spring} \geq F_a$: no motion
2) $F_{spring} < F_a$: the bearing moves in the compression direction of spring.

F_a depends on the external torque, which is generated by unexpected collisions as well as by the payload. Therefore, whether Spring-Clutch acts as a rigid joint depends on the external torque applied to the joint. Figure 2 shows the design of Spring-Clutch. The proposed Spring-Clutch mechanism consists of coil springs with a ball bearing, a CAM plate, and a linear guide. The CAM plate has two symmetric openings that have three distinctive features (indicated by red ellipses in Fig. 2). Part A allows Spring-Clutch to act as a rigid joint, as shown in Fig. 1. Part B generates free joint motion. This part is shaped like a constant radius arc to ensure that no torque is generated by the spring once the CAM plate begins to rotate. In part C, the distance to the axis decreases and the coil spring is compressed as the deflection increases. The compressed spring and the shape of the openings on the CAM plate cause a torque to be generated that counteracts the external torque. When the external torque is removed, the torque generated by the CAM plate and spring cause the CAM plate to rotate back to a neutral position. The CAM plate is symmetric to permit both clockwise and counterclockwise rotation.

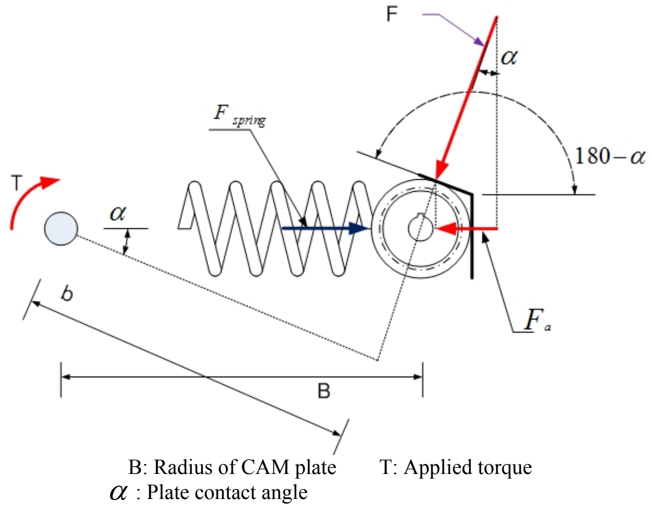

Fig. 3. Schematic relationship between design parameters for the yield torque.

Figure 3 shows a schematic of Spring-Clutch. Because it is symmetric, only one side is shown. The relationships among the design parameters in Fig. 3 are as follows:

$$F = \frac{T}{b} = \frac{T}{B \cdot \cos(\alpha)} \tag{3}$$

$$F_a = F \cdot \sin(\alpha) = \frac{T}{B \cdot \cos(\alpha)} \cdot \sin(\alpha) = \frac{\tan(\alpha)}{B} T \tag{4}$$

$$F_{spring} = F_a = \frac{\tan(\alpha)}{B} T \tag{5}$$

$$T = \frac{B}{\tan(\alpha)} F_{spring} = \frac{B}{\tan(\alpha)} Ke \tag{6}$$

where K is the spring constant and e is the compressed length of the spring. When Spring-Clutch acts as a rigid joint, $F_{spring} = F_a$. Therefore, the yield torque T is given by (6). Note that the yield torque is determined by the design parameters. Thus, with the exception of part B, large changes to the yield torque can be made by making slight modifications to the mechanical parts.

Figure 4 shows how Spring-Clutch works. In step 1, when the external torque is less than the yield torque, Spring-Clutch acts as a rigid joint. In step 2, deflection occurs because the external torque exceeds the yield torque. This deflection can be easily detected by attaching a small sensor, such as a Hall sensor, to the CAM plate. When the rotation of the link is detected, the manipulator moves to avoid collision. When the external force is removed, the CAM plate rotates back its original position due to the torque of the compressed spring on the other side.

III. THE DEVELOPED SPRING-CLUTCH

Figure 5 shows the 3D design and parts of Spring-Clutch. Figure 5(b) shows the three main parts of Spring-Clutch. Part (A) is the input part that is connected to a motor or a gear. Part (B) is the mechanism that causes the CAM plate to rotate and to reinitialize its position. Part (C) is the part of the CAM plate that connects to a link of a manipulator. Parts (A) and (C) are usually imbedded onto pre-existing manipulator frames. This means that the only additional part required to make a safe joint is part (B), which does not substantially increase the weight or size of the system. This is the most important advantage of the Spring-Clutch system.

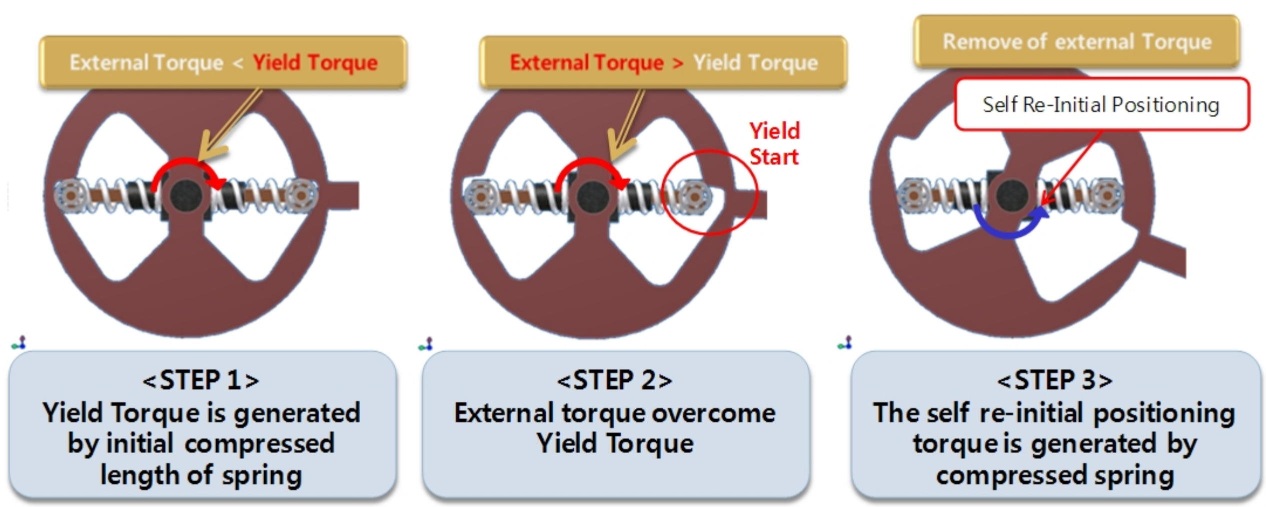

Fig. 4. Working concept of Spring-Clutch

TABLE I
SPECIFICATIONS OF SPRING-CLUTCH

Parameter	Value
Size	92 × 55 × 30 mm
Weight	220 g
Yield torque	4 Nm

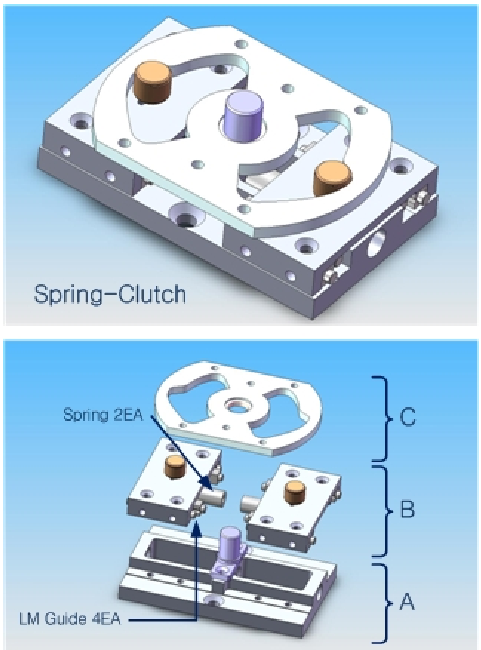

Fig. 5. 3D design and parts used in Spring-Clutch

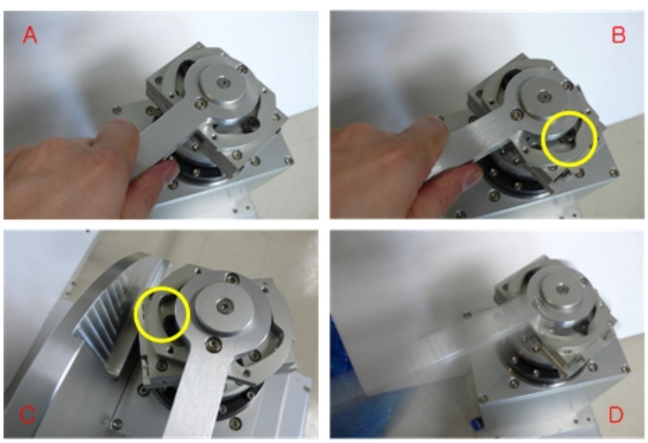

Fig. 6. Operating procedure of Spring-Clutch

Table I lists the mechanical specifications of Spring-Clutch. The weight represents the weight of the additional parts required to realize a safe joint. The yield torque is 4 Nm, which is the value selected for our safe manipulator. Figure 6 shows how Spring-Clutch works. In the first step (step (A)), Spring-Clutch acts as a rigid joint because the external force is less than the yield torque. In step (B), the CAM plate begins to rotate due to the external torque, while in step (C) the compressed spring begins to reinitializes the position. Finally, reinitializing the position occurs in step (D).

IV. PERFORMANCE EVALUATION OF SPRING-CLUTCH

In this section, the performance of Spring-Clutch as a safe joint mechanism is evaluated for static and dynamic collisions.

A. Performance of Spring-Clutch in static situations

To evaluate the performance of Spring-Clutch, a single link-joint testing mechanism was developed (see Fig. 7). A Force-Torque sensor on the mechanism and a single link, for which the length is known, are used to measure the torque applied to the safe joint mechanism. Two experiments were performed. In experiment 1, the input torque of Spring-Clutch was controlled by controlling the motor current, and the displacement of Spring-Clutch was measured. The yield torque can be accurately evaluated in this test (the design value for Spring-Clutch is 4 Nm). The results are presented in Fig. 8. The measured yield torque was 3.7 Nm, which is close to the design value.

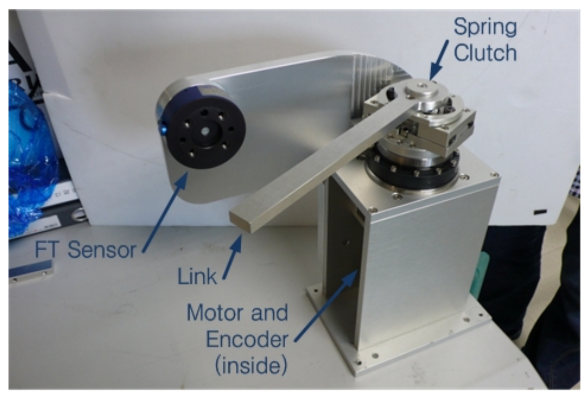

Fig. 7. Experimental device for Spring-Clutch

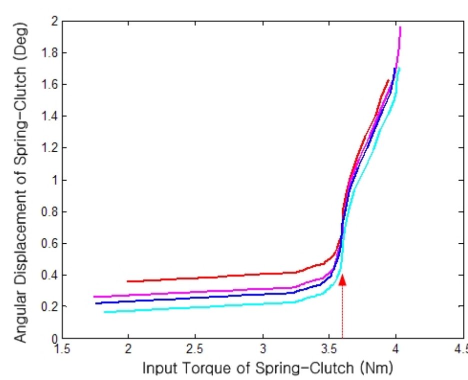

Fig. 8. Measurement of the yield torque of Spring-Clutch

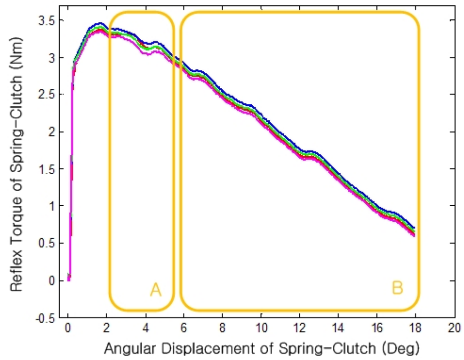

Fig. 9. Experimental results for the reflex torque

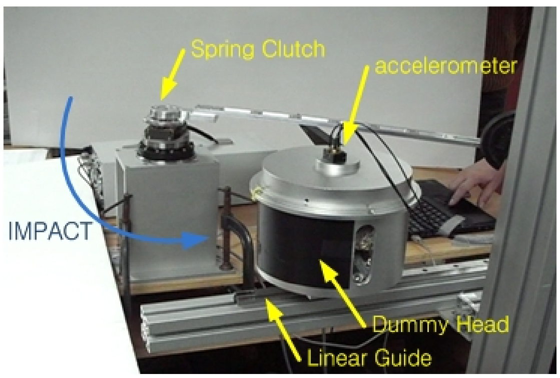

Fig. 10. Experimental setup for simulating a collision

TABLE II
EXPERIMENTAL CONDITIONS FOR COLLISION FORCE

Parameter	Value
Link Collision Velocity	1.0 m/sec
Link Head Weight	0.8 kg
Dummy Head Weight	5.0 kg

In experiment 2, the angular displacement of the link was controlled, and the reflex torque from Spring-Clutch was measured using an FT sensor (see Fig. 9). This reflex torque is the torque applied to a person's body or an object after yield motion, and is used to reinitialize the position of Spring-Clutch. For this reason, a suddenly lower magnitude for the reflex torque at that instant after yield motion (such as that of block (A) in Fig. 9) is more suitable for a safety. And the magnitude of the reflex torque, which is usually used for re-initializes, of block (B) in Fig. 9 should be determined based on the intended purpose of the manipulator like weight of link or payload. The optimization of Spring-Clutch after yield motion to satisfy the above requirements is the next research step.

B. Performance of Spring-Clutch in dynamic collisions

Basically, Spring-Clutch is designed to solve a static contact problem. However, the developed mechanism has the properties of a passive mechanism, because all the components of Spring-Clutch consist of passive mechanical parts such as springs. A passive mechanism has some advantages in reducing the collision force [6]. The experimental device shown in Fig. 10 was used to evaluate the ability of Spring-Clutch to absorb the collision force. Table II lists the parameters used in a collision experiment involving Spring-Clutch. The link with some weight parts is rotated by a joint mechanism containing Spring-Clutch, and the parameters are selected to simulate a collision with a person's head. The experiments were executed with and without Spring-Clutch. Figure 11 shows the results of this experiment. When Spring-Clutch was not used, the joint locked like a rigid joint.

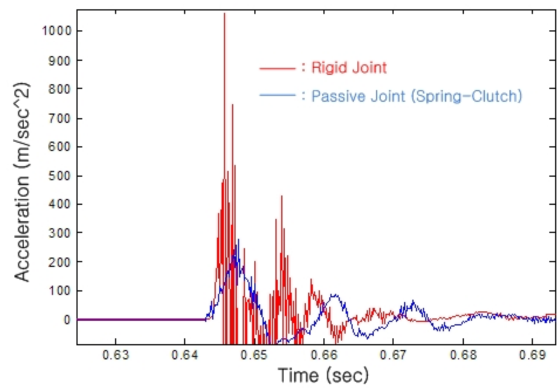

Fig. 11. Results of collision experiments

The results in Fig. 11 reveal that the acceleration distribution obtained for a passive joint is considerably lower than that for a rigid joint. The results show that Spring-Clutch can absorb the collision force. When a rigid joint was used, the maximum collision acceleration was 1063.6 m/sec^2 and the average collision acceleration was 43.18 m/sec^2. However, when Spring-Clutch was used, the maximum collision acceleration was 277.8 m/sec^2 and the average collision acceleration was 8.54 m/sec^2. According to these figures, Spring-Clutch absorbs 75–80% of the collision force, thereby demonstrating its effectiveness as a safe joint mechanism for dynamic collisions.

V. CONCLUSIONS

This paper presents a simple and robust safe joint mechanism (called 'Spring-Clutch') based on springs and a CAM mechanism. Spring-Clutch functions as a rigid joint when the applied torque is less than a predefined yield torque. Any excess torque is absorbed by angular displacement of Spring-Clutch. In addition, Spring-Clutch is able to reinitialize its position. These three important characteristics of the proposed mechanism make it suitable for constructing a safe robot manipulator. The performance and working procedure were evaluated via static and dynamic experiments.

However, the predesigned yield torque value cannot be adjusted when a manipulator is working, and the applied torque changes continuously with the posture of the manipulator and the position of the payload. In this case, a high predefined yield torque is necessary when Spring-Clutch is attached to the base axis of a manipulator. A value high enough to ensure precise and smooth manipulation is too high to guarantee safe operation of a manipulator. This is a limitation of Spring-Clutch. However, at the axis near the end effector, the torque shows little variation with the posture of the manipulator; consequently, a suitable yield torque can be calculated by taking into account the payload and the weight of the end effector. When Spring-Clutch is attached at the axis near the end effector, it can reduce the collision force and disturbances caused by position errors of the manipulator. This ability of Spring-Clutch is one of most important requirements for a robot to be used as a practical service robot.

We are currently developing a safe robot manipulator to perform public service tasks. Spring-Clutch will be attached at the axis near the end effector after optimization. In addition, a variable stiffness joint, as developed in a previous study [9], will be attached to the base joint axis. This will allow a safe manipulator to be developed that can be utilized in practical service areas.

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