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Passive Collision Force Suppression Mechanism for Robot Manipulator

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Abstract— **This paper presents a robot manipulator with collision force suppression mechanism that can passively suppress collision force. The collision suppression mechanism consists of a release air pad, a transmission rack, a clutch gear and a compression spring. An air cushion bag is attached to the exterior of the robot manipulator. If a robot manipulator collides with an object or human when a task is performed, the collision force suppression mechanism disjoints the specific joint corresponding to the direction of the collision force to reduce the collision force. The robot manipulator will then return to the former task when the colliding object is eliminated. Through collision experiments, the effectiveness of the collision force suppression mechanism is verified.**

I. INTRODUCTION

Industrial robot arms and humanoid robots are being used to increase productivity in factories. In the future, human-robot interaction is expected in the field of medical care and welfare of the tertiary sector [1]-[4]. In this field, robots will collide with humans and objects frequently. Therefore, it is important to consider the safety implications of these collisions when integrating robots into a human environment. Previous safety mechanisms avoids a collision by using various sensors that measure position and distance[5,6]. This method assumes that collisions between the human and robot do not occur, so if a collision were to happen, the human may be injured. This previous method cannot be applied in a human-robot environment. Therefore, a new robotic system that does not injure humans when a robot collides with a human is necessary.

In recent years, various methods have been proposed to address this issue. The mechanical impedance adjuster that is equipped with linear springs and break systems was proposed [7]-[11]. The joint mechanism that uses ER/MR fluid was also proposed to improve human safety [12]-[15]. However, these methods are difficult to guarantee human safety. For example, if a robot has sensing errors or if the power supply is disconnected, it would be difficult to ensure human safety.

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The method of using a soft material around the exterior of the robot was proposed [16]. The soft material absorbs the collision force when a robot collides with an object or human, leaving the human unharmed. However, the soft material does not ensure human safety when the human is sandwiched between the robot and a wall. The spring-clutch mechanism that consists of coil springs, a ball bearing, a CAM plate and a linear guide was developed [17]. The safe link mechanism that consists of a double-slider mechanism, a liner spring and a module-wire system was also proposed [18]. The passive trunk with springs and dampers was developed to improve human safety [19]. The passive collision force mechanism which consists of an inner disk, outer disks, compression springs, and a linear motion guide was developed [20]. However, these mechanisms are limited to the direction of the collision force.

In this paper, we apply air bags to absorb the collision force and we propose a passive collision force suppression mechanism without electrical control for the robot manipulator. Our proposed mechanism is installed in the joint of the robot manipulator. Through collision experiments, the effectiveness of the collision force suppression mechanism is verified.

This paper is organized as follows. Section 2 describes a new collision suppression method for human safety. Section 3 describes a robot manipulator with a collision force suppression mechanism and a collision force suppression mechanism system. Section 4 describes the control system. Section 5 describes the collision experiments. Section 6 provides the conclusions.

II. COLLISION FORCE SUPPRESSION METHOD

Many conventional robots used hard material for the exterior, and high-speed motor was converted to high torque by using the reduction gears of a high ratio. If these robots collide with a human, the human will be injured because of the high collision force and contact force (Fig.1 (a)). Therefore, we propose the method of absorbing and suppressing collision force and contact force at the time of the collision. One solution for absorbing collision force is to use a soft material, like human skin, around the exterior of the robot. This will reduce the collision force a little at the time of the collision. In order to improve human safety, we propose the passive collision force suppression mechanism that is installed in the joint of the robot manipulator.

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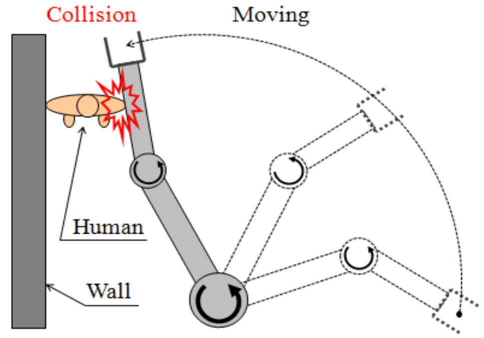
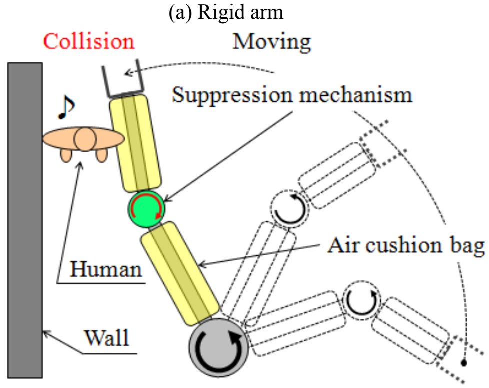


(a) Rigid arm



(b) Arm with suppression mechanism

Figure 1. Collision between arm and human.

III. Robot Manipulator with Collision Force Suppression Mechanism

A robot manipulator for human-friendly robots is developed to ensure human safety. Figure 2 shows the overview of the manipulator. It is composed of a 2-DOF shoulder, a 1-DOF elbow, and a 2-DOF hand. A collision force suppression mechanism is installed in the 2-DOF of the shoulder and in the 1-DOF of the elbow. The height of the manipulator is 880 [mm]. The movable angles of the shoulder pitch and roll are ±180 [deg] and +180 [deg], respectively. The movable angle of the elbow pitch is +135 [deg], and the movable angle of the hand roll is +90 [deg]. A collision force suppression mechanism is installed the 2-DOF of the shoulder and in 1-DOF of the elbow as shown in figure 3. Air cushion bags cover the exterior of the robot. A rotary encoder is installed to each collision force suppression mechanism.

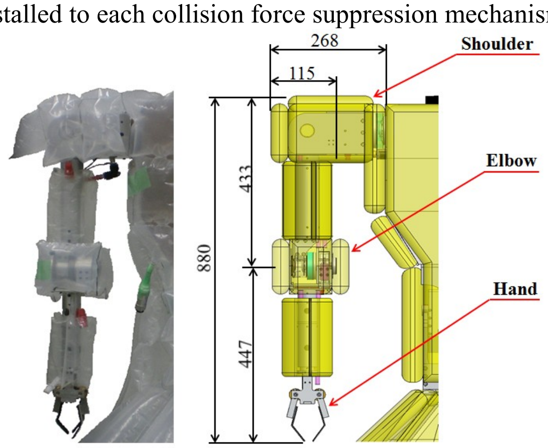


Figure 2. Robot manipulator with collision suppresion mecanism.

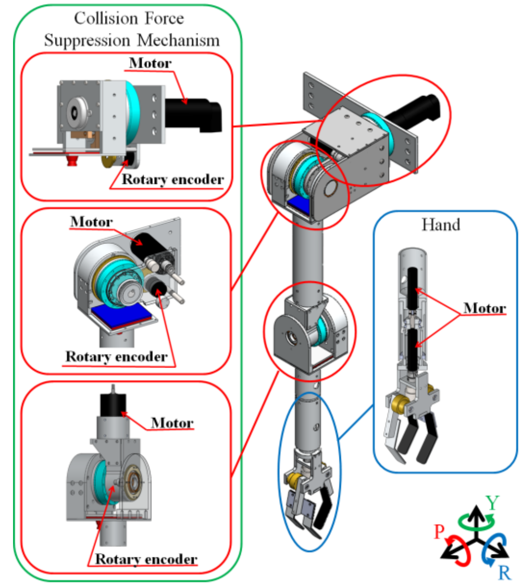
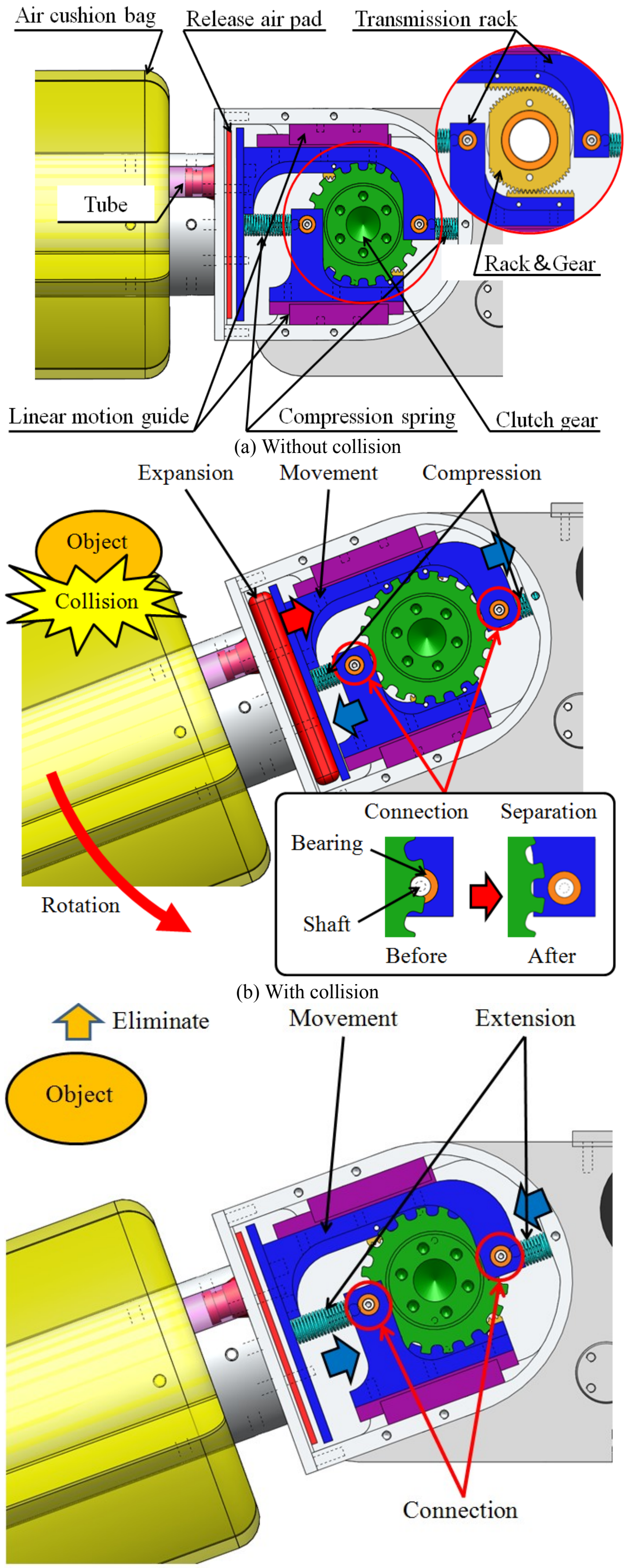


Figure 3. Positioning of the encoder and motor

A. *Collision Force Suppression Mechanism*

The collision force suppression system consists of an air cushion bag to absorb the collision force, and a collision force suppression mechanism to suppress the collision force. Figure 4 shows a cross-section view of the collision force suppression mechanism that is installed in the shoulder. Fig. 4 (a) shows the state without a collision. The transmission rack have is engaged with the clutch gear. The motor torque is transmitted to the transmission rack through the clutch gear. Therefore, the robot manipulator performs a task. Fig. 4 (b) shows the suppression state when an object or human collides with the air cushion bag. Firstly, the air cushion bag absorbs the collision force. The air in the air cushion bag is sent into the release air pad through the tube, which will then cause the release air pad to expand. Next, the transmission rack is pushed by the release air pad. The transmission rack is moved by the linear motion guide in a linear motion so that it separates from the clutch gear. As a result, the torque produced by the motor is not transmitted. Afterwards, the robot arm rotates in the direction of the collision force. By using the above mechanical movement, the robot manipulator suppresses the collision and contact force. Fig. 4 (c) shows the state after the collision. The transmission rack is reengaged with the clutch gear by using the compression springs. Thus, the robot manipulator returns to the previous task. Because two transmission racks with the shaft and the bearing are engaged with the spur gear, they separate smoothly from the clutch gear at the same time. In addition, it is possible to adjust the operating condition by changing the spring constant of the compression spring.

The multiple collision force suppression mechanism of different joints operate simultaneously by connecting a tube to another air cushion bag and release the air pad. Figure 5 shows the elbow and shoulder joint at the same time when the forearm collides with an object. Therefore, our proposed collision force suppression system can ensure a high level of human safety.



(a) Without collision

(b) With collision

(c) After collision

Figure 4. Collision force suppression mechanism system.

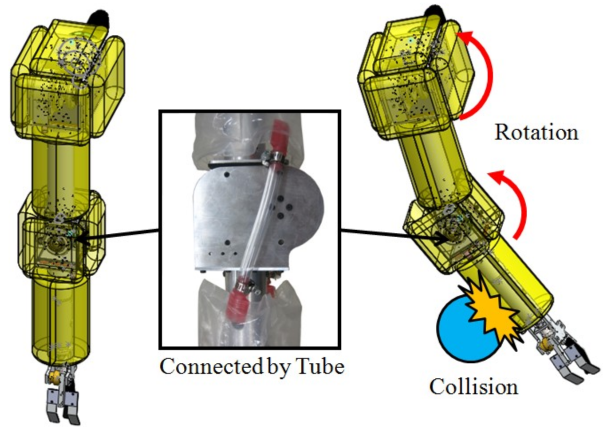


Figure 5. Connection of air cushion bag and release air pad.

B. *Air Cushion Bag*

We use two types of air cushion bags. One is a flat type air cushion bag for the arm frame, and the other is a cylindrical type air cushion bag for the shoulder and elbow. Both air cushion bags cover the exterior of the robot manipulator to absorb the collision force. In order to verify the performance of the air cushion bag, the inner pressure change of the air cushion bag is measured. The test air cushion bag is a cylindrical type that is attached to an aluminum pipe. It has an inner diameter of 45 [mm], and an outer diameter of 120 [mm]. The air pressure sensor is installed to measure the inner pressure. The test air cushion bag is dropped on a width 70 fixed plate. The internal pressure of the air cushion bag is compared with initial internal pressures depending on the dropping heights. Four kinds of initial internal pressures of the air cushion bag were compared (101.3 [kPa], 105.0 [kPa], 110.0 [kPa], 115.0 [kPa]). Figure 6 shows the results of the experiments. The initial height is shown by potential energy in Fig. 6. Each point represents the maximum value of the pressure by the fall collision. If the initial pressure is 101.3 [kPa], 105.0 [kPa] and 110.0 [kPa], the change of inner pressure become small after 1.5 [J], 2.8 [J] and 4.5 [J], respectively. The reason that the internal pressure does not change is because the air cushion bag is deformed to the maximum. However, the internal pressure continues to change when the initial pressure is 115.0 [kPa].

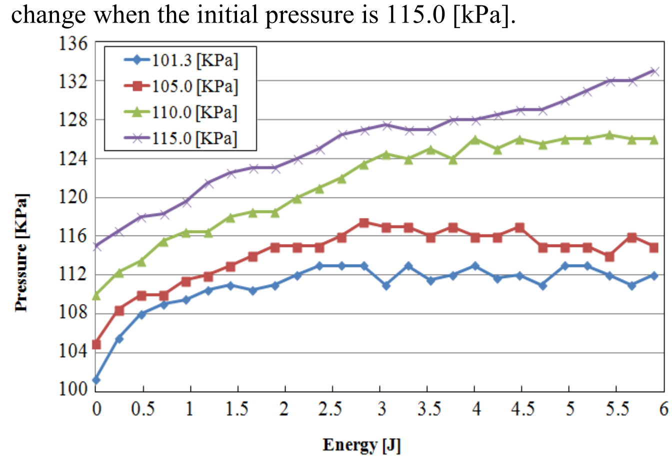


Figure 6. Collision experiments on a fixed flate: Relationship between energy and internal pressure.

The other experiments are conducted with two fixed plate (width 20 [mm] and width 70 [mm]). The initial internal pressure is 115.0 [kPa]. This experiment verifies the relationship between the internal pressure and the contact area. Figure 7 shows the experimental results. The internal pressure changes in the same amount when the energy is between 0 [J] and 2.5 [J] regardless of the contact area. Therefore, the relationship between energy and internal pressure is independent of the contact area. If the plate size is 20 [mm], the internal pressure does not change when the energy is larger than 2.5 [J] because the air cushion bag is deformed to the maximum.

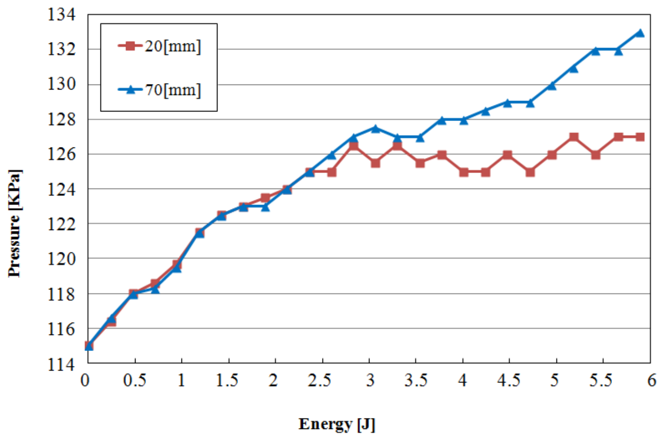


Figure 7. Collision experiments on two fixed flates: Rrelationship between energy and internal pressure.

Figure 8 shows the experimental results of the comparison of the collision force of the air cushion bag and the non-air cushion bag. The initial pressure of the air cushion bag is 105.0 [kPa]. Collision force is plotted by the maximum value. Collision force of the air cushion bag is about 4 times smaller than that of non-air cushion bag.

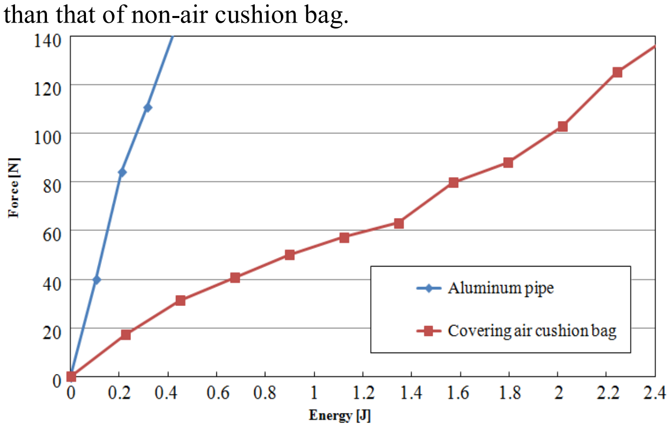


Figure 8. Collision forces in experiments of air and non-air cushion bags

C. RCOVERY TRAJECTORY CONTROL

Figure 9 shows the electrical composition of a joint. The joint of the manipulator has a spur gear, a rotary encoder and a rotary damper. A rotary damper limits the quick movement of the manipulator when a joint is released. A rotary encoder measures joint angles through the spur gear. Figure 10 shows the flow chart of the recovery trajectory control. The robot manipulator performs a task. However, when the manipulator collides with an obstacle, a joint is released by the collision force suppression mechanism. Figure 11 shows how to measure the angle error of the joint. The controller of the robot manipulator calculates the reference trajectory based on the angle error after the colliding object is eliminated. The robot manipulator returns to the previous task again.

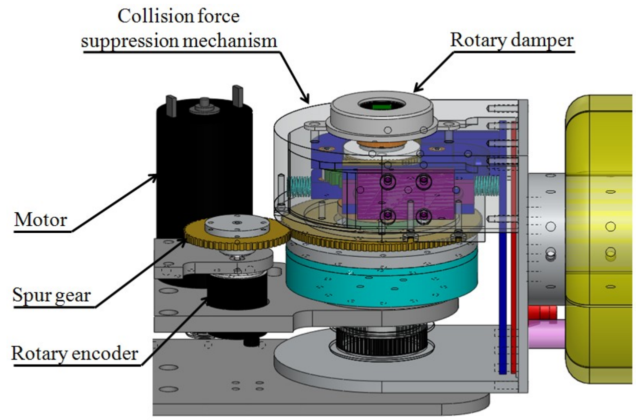


Figure 9. Mechanism of recovery system.

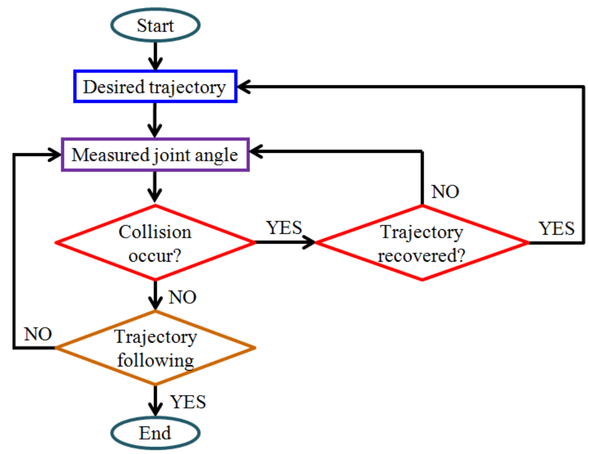


Figure 10. Flow chart of recovery trajectory.

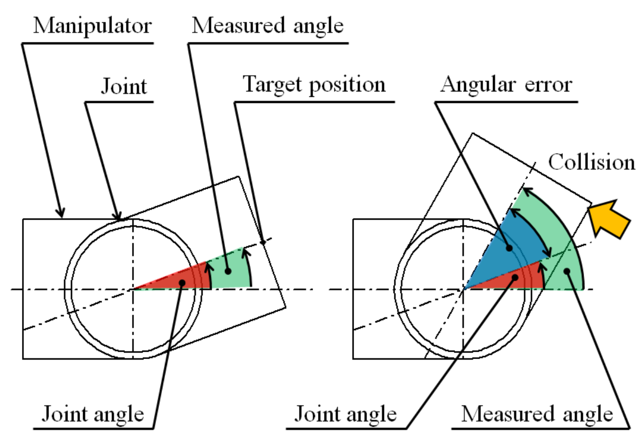


Figure 11. Measurement of angle error

IV. CONTROL SYSTEM

Figure 12 shows the electrical control system. Encoder outputs are inputted into the interface board by a counter board. The target motor torque is outputted by the voltage value from the D/A board on the PC. This robot system uses a DC-DC converter to supply power to the force sensor. The force sensor measures collision force to experimentally verify the collision force suppression mechanism, not to control the manipulator.

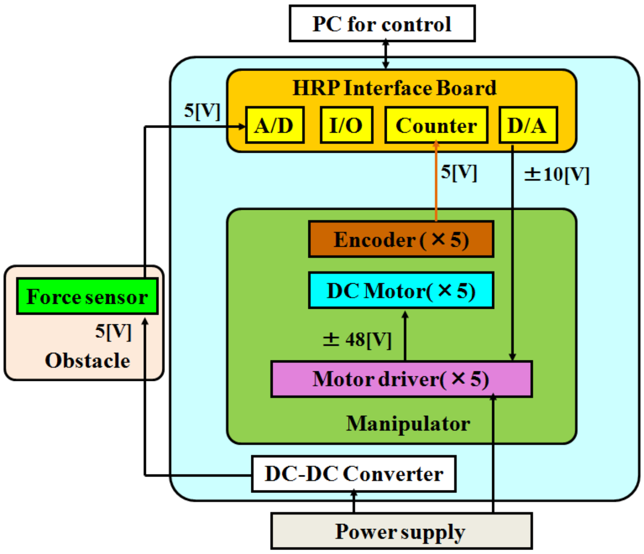


Figure 12. Electrical control system.

V. COLLISION EXPERIMENT

This section shows the collision experiments in order to verify the effectiveness of the collision force suppression mechanism that is installed in the robot manipulator. The experiment was conducted in three different conditions: (1) The manipulator without any safety mechanisms, (2) the manipulator with only an air cushion bag and (3) the manipulator with an air cushion bag and the collision force suppression mechanism. In condition (3), the initial pressure of the air cushion bag was 105.0 [kPa], and the spring constant was set for the collision force suppression mechanism to be operated when the internal pressure is larger than 106.0 [kPa]. The parameters were based on the human pain tolerance limit that is less than 30 [N] in the upper arm [21]. The human pain tolerance limit is the maximum level of pain a human can tolerate. The moving speed of the robot manipulator was 0.35 [m/s]. The robot manipulator collides with an obstacle when the robot follows a target trajectory. The collision force is measured using the force sensor attached to the obstacle.

Figure 13 shows collision forces in the experiments. The robot manipulator collides with the obstacle at 4.3 [s]. The maximum collision force in conditions (1), (2), and (3) is 50 [N], 35 [N], and 16 [N], respectively. The impact force was lower than the human pain tolerance limit of 30 [N] in only condition (3). In conditions (1) and (2), contact force occurred because the robot manipulator continuously pushed the obstacle. On the other hand, the robot manipulator in condition (3) reduced the contact force to 0 [N] because of the collision force suppression mechanism. Therefore, if a human collides with the robot manipulator with an air cushion bag and the collision force suppression mechanism, the human will be safe. Figure 14 shows the desired and measured angles of the shoulder in this experiment. The joint angle deviated from the desired angle at 4.3 [s] by operating the collision force suppression mechanism. However, the trajectory of the shoulder was returned to the target trajectory by the recovery control after 8.8 [s]. The robot manipulator continues to run when the colliding object is eliminated.

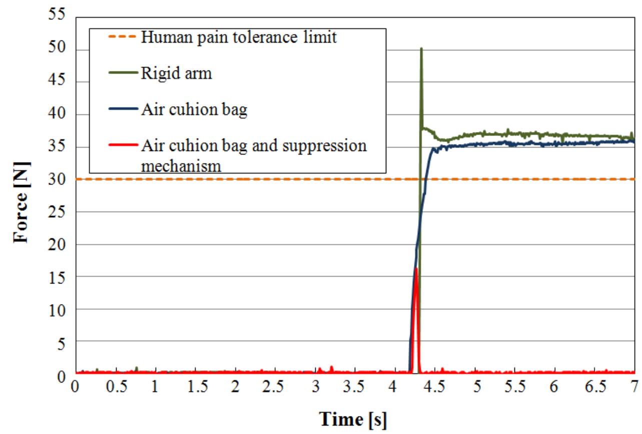


Figure 13. Experiment results *(collosion forces)*.

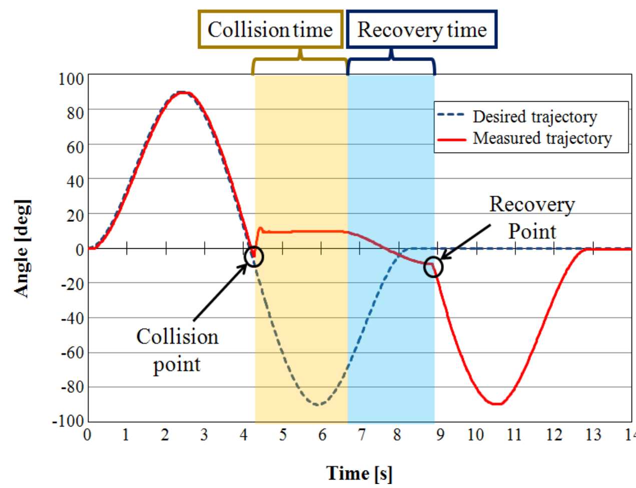


Figure 14. Experiment results *(shoulder pitch trajectories)*.

VI. CONCLUSION

In this paper we have developed a collision force suppression mechanism that can suppress collision force passively on the assumption that a robot collides with a human or object. The developed robot manipulator is composed of a 2-DOF shoulder, a 1-DOF elbow, and a 2-DOF hand. A collision force suppression mechanism is installed in the arm joint. Furthermore, air cushion bags cover the surface of the manipulator. Through collision experiments, we verified the effectiveness of the collision force suppression mechanism. This manipulator can reduce the collision/contact force to be less than the human pain tolerance limit. Moreover, we verified that the robot manipulator follows the target trajectory again by using the recovery control after the collision.

In the future, a small and lightweight suppression mechanism and a puncture resistant air cushion bag will be developed. Also, the mechanism will be installed in the waist of the human friendly robot.

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