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High-speed Hitting Grasping with Magripper, a Highly Backdrivable Gripper using Magnetic Gear and Plastic Deformation Control

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Abstract— **In this study, Magripper, a highly backdrivable gripper, is developed to achieve high-speed hitting grasping executed seamlessly from reaching. The gripper is designed to achieve both high speed and environmental adaptability. The key element is backdrivability in terms of both hardware and control. In Magripper, a magnetic gear is introduced to passively absorb shock in the moment of contact as a means of hardware backdrivability, and backdrive control is implemented based on the Zener model. After developing a hitting grasping framework, high-speed hitting grasping tasks with a wood block, a wood cylinder, and a plastic coin are conducted using only servo control without sensors, such as cameras and tactile sensors. In particular, coin grasping with high-speed movement is very difficult because collisions with environmental objects such as the floor and desk, are likely, which may break a robot.**

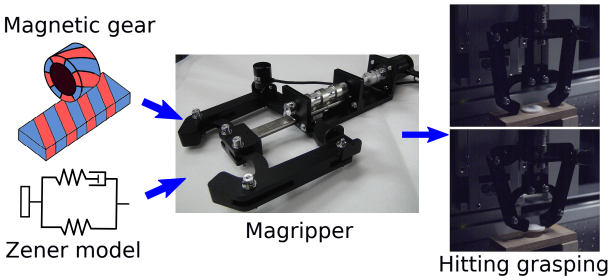

Fig. 1. Concept of hitting grasping using Magripper. Magripper is a highly backdrivable gripper with combination of a low-friction mechanism (magnetic gear) and a shock absorption control (Zener model). Hitting grasping is high-speed grasping on the assumption of hitting objects and the environment. The gripper can grasp a thin object such as a coin at high speed with seamless motion.

I. INTRODUCTION

When asked to imitate robotic motions, people perform awkward with sequential motion. Furthermore, your hand will not touch an object or environment before grasping. Such a perception of robot movements can be attributed to the hard mechanism and unsmooth movement associated with conventional robot systems that comprise motors and reduction gear. Most robotic grippers are vise-like rigid clamping using a high gear-ratio worm screw or similar transmission. Because the high gear-ratio lead to poor responsiveness and decreased backdrivability, robot systems based on geared motor break when excessive force is applied. In particular, for manipulation tasks, there are many cases where the robot gripper breaks on collision with environmental objects, such as the floor and wall, preventing its interaction with the environment. Moreover, conventional robot systems are taught motion trajectories in advance by operators to avoid obstacles. Therefore, conventional robot systems move slowly and awkwardly with repetitive patterns.

To overcome these problems and achieve smooth robot interaction with the environment, direct drive motors (DD-motors) with high backdrivability can be used [1]. However, even such robots may perform awkward and slow movements because many automatic robot systems use obstacle avoidance and object sensing. Because adaptation to changes in the environment and objects is difficult to achieve with position control by teaching, obstacle avoidance and object manipulation with grippers have been investigated using object sensing approaches such as machine learning [2]–[4]. However, high-speed motion cannot be achieved because the estimation of object position and calculation of the motion plan demand high costs.

To realize high-speed interaction with environment and a gripper, it is necessary to consider damage due to collision and deflection of objects. The repulsive force when contacting objects or the environment, and the force applied at the time of collision increase with high-speed operation. In high-speed tasks, including collision with the environment, the possibility of the gripper being broken by the collision increases. Therefore, a gripper with a mechanism that does not break and can absorb the impact force is required. In addition, a method that seamlessly execute tasks from reaching to grasping is required to accelerate the entire operation.

Accordingly, to achieve high-speed grasping and seamless execution from reaching to grasping, we propose high-speed hitting grasping based on backdrivability as framework, unlike existing robotic manipulation approaches. The overview of this study is shown in Fig.1. The contribution of this study is the realization of high-speed hitting grasping by the development of Magripper, a new gripper with high backdrivability in terms of both hardware and control with the assumption of collision.

First, we introduce a magnetic gear and design Magripper, a highly backdrivable 1-actuator gripper, to achieve both high speed and environmental adaptability. Backdrivability and high-speed operation at the moment of contact are realized by using a DD-motor and the magnetic gear (rack and pinion type). With the high backdrivability, the contact state can be changed without flipping the object at the moment

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of contact and without breaking the gripper. At the same time, Magripper can perform high-speed position control similar to a conventional gripper driven by a motor. In addition, Magripper is composed of one actuator and can be fabricated at relatively low cost, making it suitable for factory automation applications.

Second, we implement deformation control based the Zener model [5] in Magripper as backdrive control and improve its adaptability to dynamic manipulation. The Maxwell model using mechanical elasticity and viscosity control realized the shock absorbing ability of the contact state with the object, and the Voigt model realized grasping of the object. By mounting the Zener model, which can switch between the Maxwell model and Voigt model with parameters, on the gripper, we successfully achieved higher backdrivability. To the best of our knowledge, this study represents the first real robot implementation of the Zener model control.

As the third contribution, we propose the concept of hitting grasping using Magripper, which is grasping manipulation with hitting of the environment and objects, and experimentally demonstrate its implementation in a high-speed robot system. Overall, seamless reaching and fast grasping on the assumption of hitting objects and the environment are achieved. In this manner, a different approach from the static and quasi-static approaches to avoid hitting environment could be used. In the experiments, Magripper dynamically and robustly grasped a wood block, a wood cylinder, and a plastic coin with the same strategy and same parameters. In particular, coin grasping with high-speed movement is an extremely difficult task because collisions with environmental objects such as the floor and desk are likely, and the robot may break. These could be achieved using only servo control via only encoder information without image processing, tactile sensors, or proximity sensors.

A. Related Works

- Robotic Hand

As a high-speed robotic hand, Namiki hand achieved high-speed dynamic manipulation, and contact with dynamically moving objects [6]–[8]. However, Namiki hand uses a bevel gear and a hard transmission mechanism, and its design is such that it breaks when upon hitting the environment such as the floor. Karako hand achieves the peg-in-hole task at high speed, but it has eight motors, many actuators as grippers, and is not designed to consider impact from objects [9].

DD Hand achieves object grasping while contacting the floor based on the backdrivability of a direct drive motor [10]. However, it has four direct drive motors and many actuators as grippers, which causes problems of large current and heat generation. In addition, DD Hand is not designed to to grasp thin objects such as coins.

Blue Gripper archived a gripper with high backdrivability and aimed to a low-cost gripper [11]. A remote-direct-drive 2-DOF gripper with hydrostatic linear actuator also archived high backdrivability [12]. However, these grippers are not considered to high-speed manipulation.

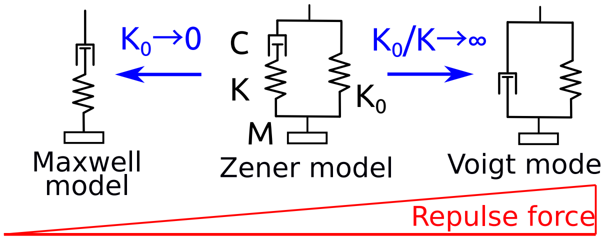


Fig. 2. Overview of relation among Zener model, Maxwell model, and Voigt model. Zener model can parameterize between Voigt model and Maxwell model. K and K_0 are spring constants. C is a viscosity coefficient. M is a mass.

In the passive mechanism hand [13], a trigger is activated at the moment of contact with the object, achieving quick object grasping using a spring etc. However, collisions with the environment and grasping thin objects are not considered in the design.

The soft material hand [14], and hands based on elastic elements such as the wire-based hand [15] achieved deformation ability and mechanical softness. Because adaptation to the environment and objects can be easily realized, safety and damage prevention could be achieved, and adaptive grasp tasks have been successfully performed for environments and objects. However, in general, a soft mechanism reduces mechanical responsiveness, speed, and position controllability, and it is difficult to realize an operation that requires the same level of dynamics as a human.

- Deformation Control

The Voigt model, in which a spring and a viscous damper are connected in parallel and is often called by impedance control, is often used to express softness. However, it does not have sufficient backdrivability because repulsion always occurs. Therefore, plastic deformation control was proposed as a control expressing softness with backdrivability [16], [17]. These studies used a control based Maxwell model, in which a spring and a damper are connected in series, was used to achieve the deflection of an external force.

In this study, we used the Zener model as backdrive control, which can parameterize between the Voigt model and Maxwell model, as shown in Fig.2 [5]. In the Zener model, the repulsive force can be adjusted by parameterization of spring constants K and K_0. When K is small enough, it becomes a Voigt model, and the repulsive force against external force can be increased and the force can be transmitted to the object. When K_0 approaches 0, it becomes a Maxwell model, and the repulsive force can be reduced. In this study, experiments were successfully performed only in simulations, and no implementation has yet been performed on actual machines.

II. MAGRIPPER

A. Design

The gripper developed in this study, Magripper, is shown in Fig.3. Magripper is based on Magslider [17]. Magripper comprises a DD-motor with high backdrivability without a speed reducer in the drive unit, and magnetic racks and

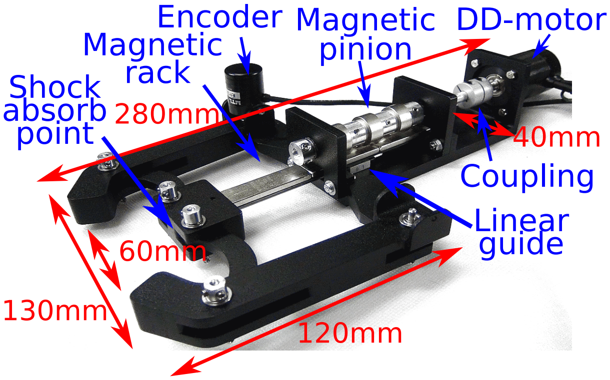
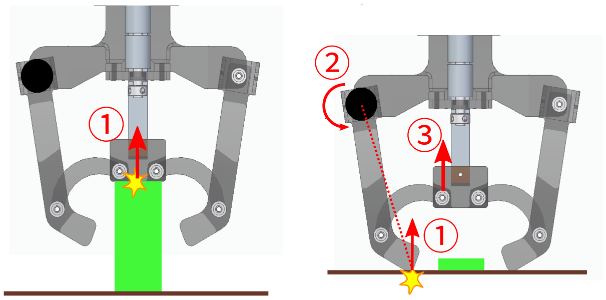


Fig. 3. Overview of Magripper. The gripper is composed of a DD-motor, magnetic pinions, magnetic racks, and link mechanisms. When an object contact to the shock absorb point, the magnetic rack easily move backward by the its backdrivability and the shock absorb control. The gripper's fingertips are closed at the same time as the back drive of the magnetic rack.



(a) (b)

Fig. 4. Link mechanism of Magripper. (a) Link mechanism while hitting objects. In case of large object, shock absorb point contact to an object and the gripper starts backdrive motion. (b) Link mechanism while hitting the environment. In case of a thin object, the gripper also starts back drive motion and grasp it automatically.

magnetic pinions as the transmission mechanism that realizes back-drivability with low friction. In the magnetic rack-and-pinion, the power from the DD-motor is converted from rotation into linear motion in the orthogonal direction. Regarding machine elements, 30 mm diameter DD-motor MDS-3018 (MTL Inc.), three 16 mm diameter magnetic pinions FD16-C-AS-A6 (FEC Inc.), and three small-sized magnetic racks of 3 mm × 12 mm × 42 mm FDR16-C-AS (FEC Inc.) were used. In addition, couplings, iron plates, linear guides, and structural materials made with 3D printers were used.

In addition to the acquisition of backdrivability, the link mechanism is an important aspect in the design of Magripper. As high backdrivability and assumption of collision are considered, we propose a shock absorption mechanism for the environment, including the floor and objects. The link design is shown in Fig.4. When coming into contact with an object, Magripper uses shock absorb points, similar to using the palms (Fig.4.(a)). When coming into contact with the environment in case of grasping a thin object, Magripper uses the tip of the gripper, similar to using the fingertips (Fig.4.(b)). Note that by link design and high backdrivability, normal force from contact to the environment (①) converts to rotational force of the link to close direction (②), and then to backdrive linear movement on the shock absorb point (③). This link design facilitates grasping with collision without tactile sensors or force sensors.

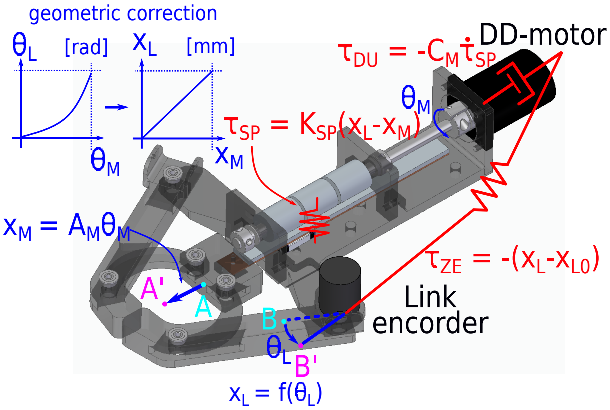


Fig. 5. Implementation of the Zener model in Magripper.

B. Zener Model Implementation

The backdrivability of Magripper is attributable not only to the high backdrivability of the magnetic gear but also backdrive control by the Zener model (Fig.5). The Zener model comprises τ_{SP}; spring force of magnetic gear, τ_{DU}; motor control to express dumper, and τ_{ZE}; motor control to express the spring force $\boldsymbol{K_0}$ in Fig.2.

First, the spring force of magnetic gear, τ_{SP}, is calculated. The linear movement value of shock absorb point x_M [mm] is calculated from the encoder in the DD-motor, which is expressed by

$$x_M = A_M\theta_M, \tag{1}$$

where A_M is the geometric coefficient from radian to millimeter, and θ_M is the value of motor encoder. From the geometric relationship of the link mechanism, the approximate value of the link encoder from the linear movement value of shock absorb point coordinate (x_L [mm]) is calculated by

$$x_L = f(\theta_L) = a_1\theta_L^{a_2}, \tag{2}$$

where f is the function of geometric correction, θ_L is the value of the link encoder, and a_1 and a_2 are geometric coefficients. Point A and B from the close state move to A' and B' in Fig.5. a_1 and a_2 were set during the experiment such that the motor rotates slowly, and in this study a_1 is 0.265 and a_2 is 0.6. After the calculation of x_M and x_L, the torsion torque between magnetic gear τ_{SP} is calculated by

$$\tau_{SP} = K_{sp}(x_L - x_M), \tag{3}$$

where K_{sp} is the coefficient of spring elasticity.

Second, the motor control to express dumper τ_{DU} is expressed using τ_{SP} by

$$\tau_{DU} = -C\dot{\tau}_{SP}, \tag{4}$$

where C is the coefficient of damper viscosity.

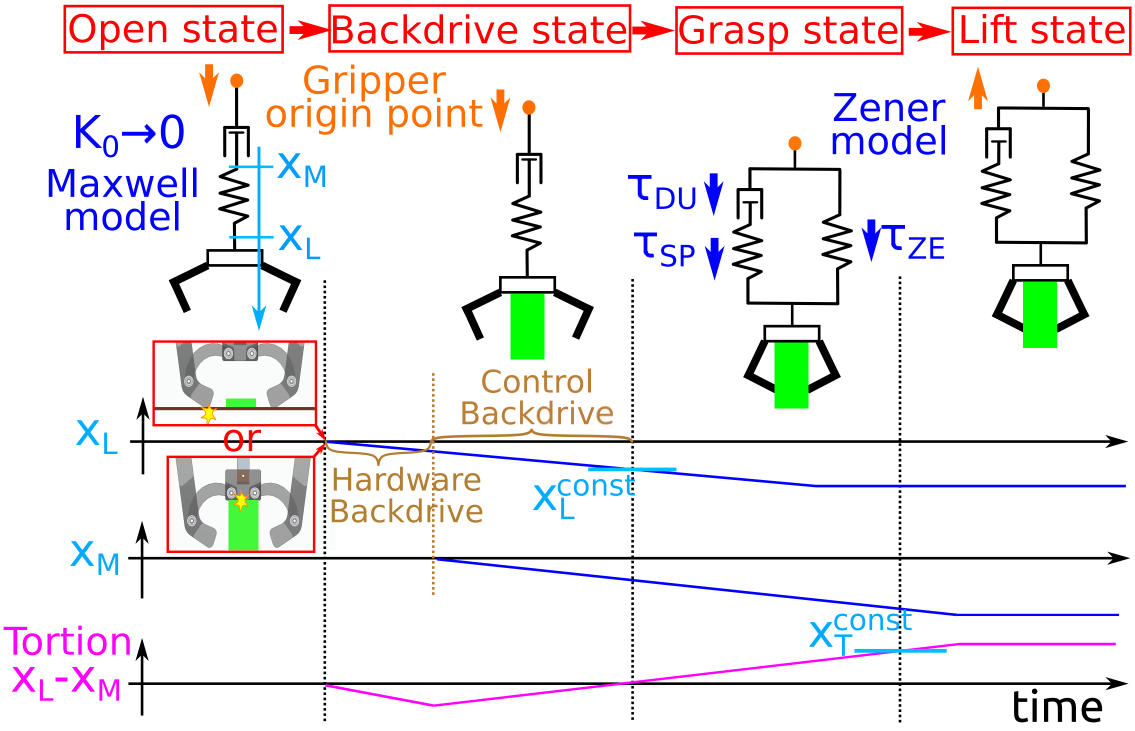


Fig. 6. Overview of the hitting grasping. The open state changes to the backdrive state when Magripper hits an object or the environment. The backdrivability of the magnetic rack-and-pinion responded immediately after impact. After hardware backdrive, Magripper absorbs the impact from an object or environment by backdrive control based on the Maxwell model, which is K_{ZE} = 0 in the Zener model. In the backdrive state, the Magripper origin point continues moving towards the object. The backdrive state changes to the grasp state under $x_L < x_L^{const}$, when Magripper detects objects or the environment. In the grasp state, the Zener model control is applied to Magripper to apply repulsive force to an object in order to grasp the object. In the grasp state, the origin point of Magripper stops. The grasp state changes to the lift state under $x_L - x_M < x_T^{const}$, which means that grasp force is enough to transmit an object. In the lift state, the origin point of Magripper moves to the initial point.

Third, the motor control to express spring force $\boldsymbol{K_0}$, τ_{ZE} is expressed by

$$\tau_{ZE} = K_{ZE}(x_L - f(\theta_{L0})), \tag{5}$$

where θ_{L0} is the equilibrium length of the link encoder, and we set the value at the close state in this paper. Therefore, the input torque to the motor τ_M is expressed by

$$\tau_M = \tau_{DU} + \tau_{ZE}. \tag{6}$$

C. Hitting Grasping

In this study, we propose hitting grasping using Magripper. An overview of hitting grasping is shown in Fig.6. hitting grasping consists of four states, open state, backdrive state, grasp state, and lift state.

The open state changes to the backdrive state when Magripper hits an object or the environment. Hardware backdrive, the backdrivability of the magnetic rack-and-pinion, responded immediately after impact. At the time of hardware backdrive, only the link encoder x_L enters the backdrive state and the motor encoder does not backdrive. Therefore, the spring between the magnetic rack-and-pinion is compressed. After hardware backdrive, Magripper absorbs the impact from an object or environment by backdrive control based on the Maxwell model, which is K_{ZE} = 0 in the Zener model. In the backdrive state, Magripper continues moving towards the object via a robot arm or linear slider.

The backdrive state changes to the grasp state under the condition of the link encoder, $x_L < x_L^{const}$, when Magripper detects objects or the environment. The Zener model control is applied to Magripper to apply repulsive force to an object in order to grasp the object. The motor pulls the shock absorb point, and then the spring between the magnetic rack-and-pinion is extended. In the grasp state, the robot arm or linear slider stops, and the origin point of Magripper stops.

The grasp state changes to the lift state under the condition in the torsion of the magnetic rack-and-pinion, $x_L - x_M < x_T^{const}$, which means that grasp force is enough to transmit an object. In the lift state, the robot arm or linear slider moves to the initial point.

III. EXPERIMENT

A. Setting

In the experiment, Magripper grasped three different objects, a wood block in section III.B, a wood cylinder in section III.C , and a plastic coin in section III.D. The dimensions of the wood block was 15 mm × 30 mm × 60 mm, and the weight was 7 g. The dimensions of wood cylinder was ϕ 40 mm and 80 mm height, and the weight was 70 g. Regarding object characteristics, a lying wood cylinder is difficult for the suction mechanism to handle because the upper side is a curved surface. The dimensions of the plastic coin made of acrylic was ϕ 30 mm and 3 mm height, and

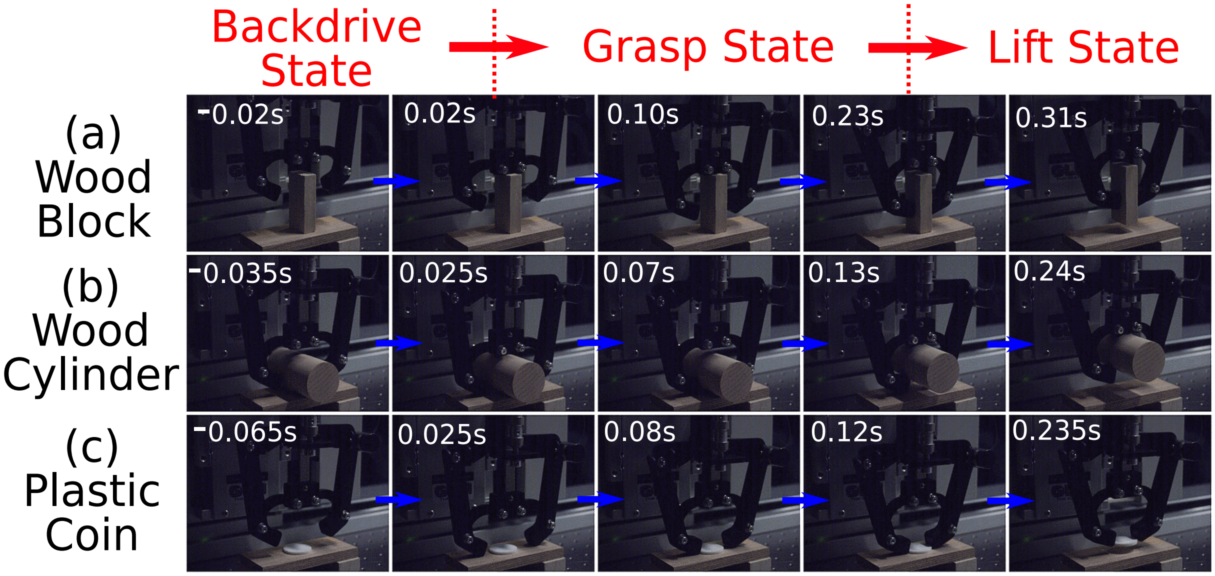


Fig. 7. Overview of the hitting grasping experiment.

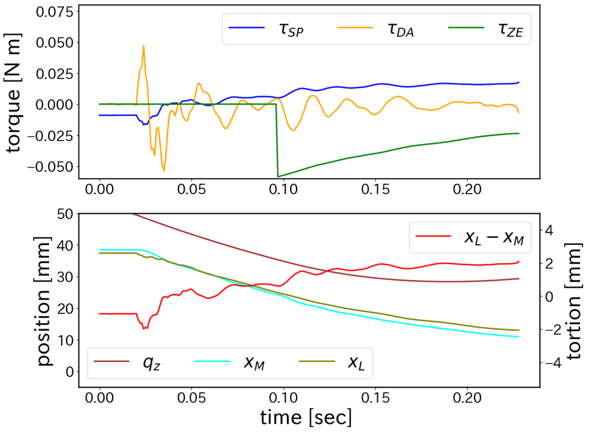


Fig. 8. Time response of the wood block grasping. Upper figure: Zener model control, τ_{SP} is the spring force of the magnetic gear, τ_{DU} is motor control to express dumper, τ_{ZE} is motor control to express the spring force of $\boldsymbol{K_0}$ of the Zener model in Fig.2. Lower figure: encoder value, q_z is the position of z-axis linear actuator, x_L is the value of link encoder from the linear movement of shock absorb point coordinate, x_M is the linear movement value of shock absorb point, $x_L - x_M$ is torsion of magnetic rack-and-pinion.

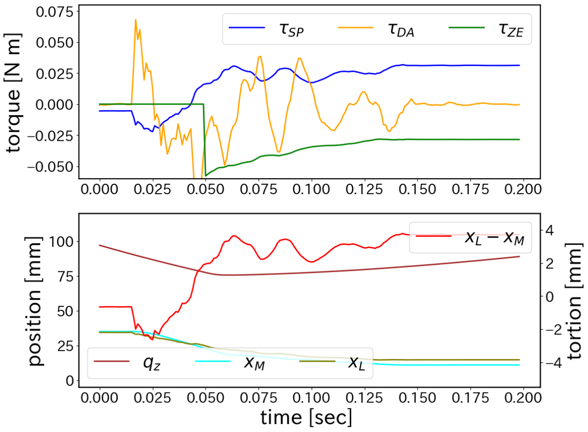


Fig. 9. Time response of grasping task for the wood block placed on a floor of different height. The labels are the same as in Fig.8.

its weight was 3 g. Regarding object characteristics, a plastic coin is difficult for the conventional gripper mechanism to grasp at high speed because the gripper is prone to breakage when hitting the environment at high speed.

In this study, Magripper was attached to 2-axis linear actuators, GLM10-M Series (THK Inc.). The roulette betting task in section III.D used the 2-axis actuator, and the others task used only a z-axis actuator. The 2-axis actuator and Magripper are controlled by a real-time controller, dSPACE, within 1 ms every control cycle. In addition, the parameters were set as follows: $K_{SP} = 10.0$, $K_{DU} = 6.0$, and $K_{ZE} = 3.5$, x_L^{const} = -0.020, x_T^{const} = 0.001.

B. Wood Block Grasping

The continuous picture in Fig.7 (a) shows grasping of the wood block. It can be confirmed that the shock absorb point was hit first and Magripper grasped the object while absorbing impact. Fig.8 shows the time response of Magripper. The Maxwell model control responded in the backdrive state until 0.097 s. The damper viscosity responded immediately after impact, and the spring elasticity responded gradually. After satisfying the threshold condition, Zener model control responded in the grasp state from 0.097 s to 0.140 s. The Zener term confirms that the force for grasp was applied. After satisfying the threshold condition, Magripper transitioned to the lift state.

Next, the grasping task was conducted under the condition that floor height is increased by about 45 mm. Fig.9 shows the response of Magripper. Similar to Fig.8, the damper viscosity responded immediately after impact, and the spring

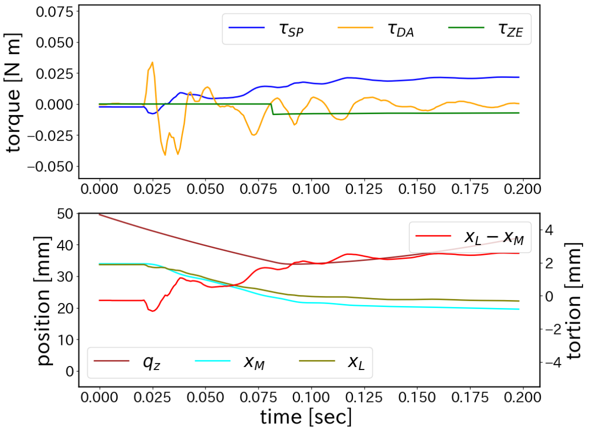


Fig. 10. Time response of grasping task for the wood block when K_{ZE} = 0.5. The labels are the same as in Fig.8.

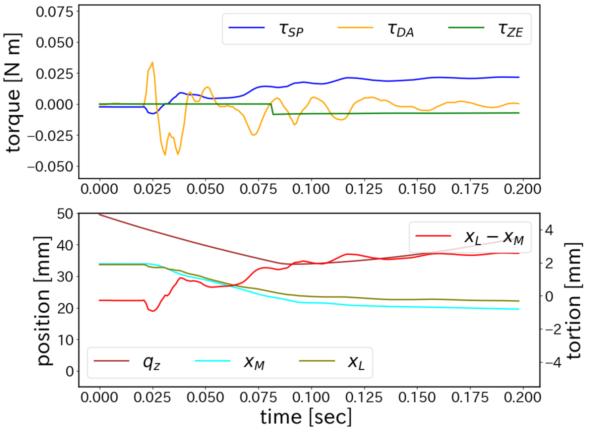


Fig. 11. Time response of grasping task for the wood block when K_{ZE} = 10.0. The labels are the same as in Fig.8.

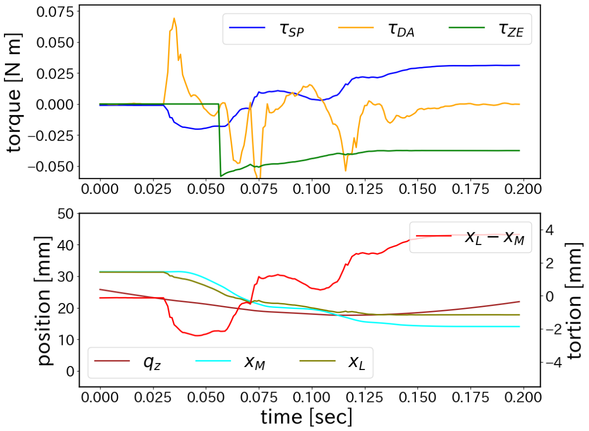


Fig. 12. Time response of grasping task for the wood cylinder. The labels are the same as in Fig.8.

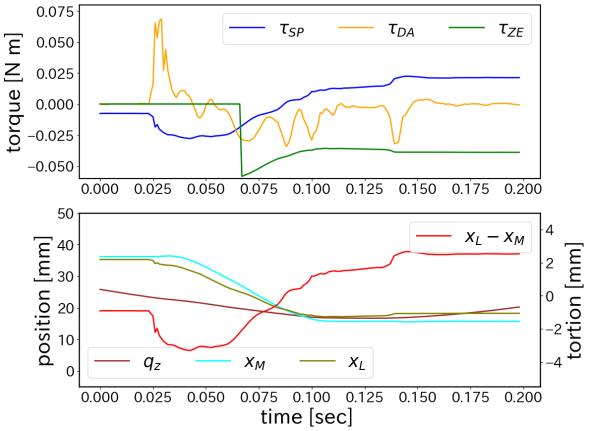


Fig. 13. Time response of grasping task for the plastic coin. The labels are the same as in Fig.8.

elasticity responded gradually. However, the vibration of damper viscosity was larger, which could be attributed to variations of the magnetic pole in the magnetic rack-and-pinion. The vibration was considered to be actualized from larger impulse.

In addition, the grasping task was experimented with different parameters of K_{ZE}. For K_{ZE} of 0.5, the time response is shown in Fig.10. The object dropped in the lift state because the grasping force of τ_{ZE} was not sufficient to grasp the object. For K_{ZE} of 10.0, the time response is shown in Fig.11. The object dropped in the lift state because the magnetic gear stepped out and the shaft of the encoder idled, which is shown in the encoder response of Fig.11. Experiments with these different parameters showed that the parameters should be adjusted to achieve a torque that does not cause the step-out of the magnetic gear and that can grip the object with sufficient grasping force.

C. Wood Cylinder Grasping

Grasping an object of different shape with the same parameters in the wood block was successful, and Magripper could grasp an object heavier than the wood block. The continuous picture of grasping the wood cylinder is shown in Fig.7 (b), and Fig.12 shows the time response. It is confirmed that the vibration of damper viscosity is larger in Fig.12. This is considered to be attributable to the object shape, which suggests that the impact to the shock absorb point occurred at the moment of grabbing.

D. Coin Grasping

Even though the plastic coin is difficult to grasp because grasping thin objects at high speeds increases the possibility of colliding with the desk or the floor, the coin grasping task was completed successfully with the same parameters as the wood block and the wood cylinder. A continuous picture is shown in Fig.7(c), and Fig.13 shows the time response. It is confirmed that the time response is similar to those of grasping other objects even when Magripper hit the objects and environment differently, and grasping the coin was achieved with the same framework.

As a demonstration, the high-speed roulette betting task was also performed; high-speed grasping for the coin on felt was achieved. A continuous picture is shown in Fig.14. The task was completed within 1 s.

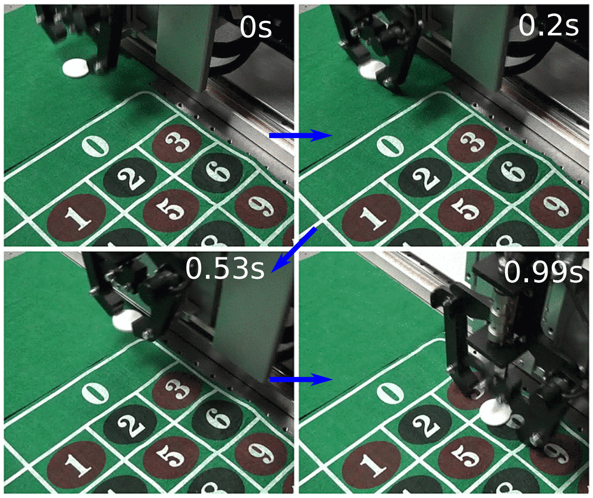


Fig. 14. Overview of continuous sequence of pictures of the roulette betting task.

IV. CONCLUSION

In this study, to realize high-speed and seamless grasping, we developed Magripper and a hitting grasping framework. Magripper archived high backdrivability by using a magnetic rack-and-pinion and implementing the Zener model control as backdrive control. After developing a hitting grasping framework, high-speed hitting grasping experiments for various objects including coins were archived.

Future works will focus on (1) construction of a regrasping algorithm with step-out detection, (2) construction of an optimization algorithm for the Zener model parameter in Magripper, (3) hardware update to Magripper to achieve higher backdrivability, and (4) construction of an reaching algorithm for hitting grasping using Magripper.

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