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Grasp Force Magnifying Mechanism for Parallel Jaw Grippers

Takeshi Takaki and Toru Omata

Abstract— **This paper proposes a force magnifying mechanism for a parallel jaw gripper that can exert a large grasp force. A parallel jaw gripper requires speed when opening and closing its jaws, and force when grasping an object. The proposed force magnifying mechanism consists of a slider, feed screws, gears, a lever, etc. It runs sequentially with only one DC-motor. Basically the motor rotates a feed screw to move its output jaw quickly to an object with a gear. When the output jaw makes contact with an object, the gear is loosened from a stopper and starts to move axially along the feed screw. Then it pushes a lever, which generates a large fingertip force. We have developed an 86g gripper with this mechanism and experimentally verified that it can grasp objects of various sizes with a large grasp force over 200N. It is also experimentally verified that the gripper can grasp and ungrasp an object reliably over 4500 times if machine lubricant is properly supplied.**

I. Introduction

In the industrial field, a large number of parallel jaw grippers are used for manufacturing and assembly robots. They require force when grasping an object and speed when opening and closing their jaws. For the power transmission of a parallel jaw gripper driven by an electric motor, a feed screw or a cam is used and its reduction ratio is usually constant. Therefore to satisfy the force and the speed performances simultaneously, a large motor is necessary, or if the reduction ratio is made large, the speed of the jaw becomes slow. Generally, a parallel jaw gripper is installed at the end of a manipulator as an end-effecter. If a parallel jaw gripper can be made lightweight, it can not only exert a large grasp force, but also reduce the load of the manipulator.

A gripper or a robot hand requires only unidirectional force for grasping. By focusing on this fact, we have already proposed a five-linkage continuously variable transmission for revolute joints of a finger, which can satisfy the force and the speed performances simultaneously[1][2]. This paper also focuses on this fact and proposes a grasp force magnifying mechanism for the linear motion of a parallel jaw gripper. It consists of a slider, feed screws, gears, a lever, etc. It runs sequentially with only one DC-motor. Basically the motor rotates a feed screw to move its output jaw quickly to an object with a gear. When the output jaw makes contact with an object, the gear is loosened from a stopper and starts to move axially along the feed screw. Then it pushes a lever, which generates a large fingertip force.

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We have developed an 86g gripper with this mechanism and experimentally verified that it can grasp objects of various sizes with a large grasp force over 200N. It is also experimentally verified that the gripper can grasp and ungrasp an object reliably over 4500 times if machine lubricant is properly supplied.

The robot hand in [3][4] has a similar mechanism consisting of a gear and a feed screw. However, it is a shape-fitting mechanism, whereas the proposed mechanism is a grasp force magnifying mechanism. Hirose proposed a continuously variable transmission for linear motion, X-screw [5]. It is a general purposed mechanism, not developed for a light-weight and small gripper.

This paper is organized as follows. Section II presents the principle of the force magnifying mechanism. Section III shows experimental results which verifies the effectiveness of the mechanism. A general problem with screws is jamming. Section IV shows a recovery procedure and its experimental verification.

II. Principle

A. Basic principle

Figure 1 shows lever and toggle joint mechanisms, which can exert a large force. However, these mechanisms can exert a large force only near the particular position x at which the lever is down in (a) and the links stretch out in (b), respcetively. Therefore, they are not suitable for grasping objects of various sizes.

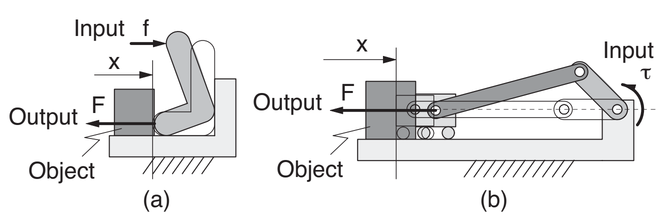

Fig. 1. Lever and toggle mechanisms

To grasp objects of various sizes with a large force, we propose a mechanism as shown in Fig. 2. It grasps an object between the fixed plate and the output jaw. Its basic principle is as follows: In (1) the motor rotates screw 1 with gears 1 and 2 to close the output jaw. In (2) when the output jaw makes contact with the object, gear 2 starts to move to the left along screw 2. In (3) and (4) gear 2 pushes the lever which in turn pushes the slider. Since the output jaw and screws 1 and 2, etc. are installed on the slider, the output jaw shifts together with the slider. Thus the output jaw pushes the object, which generates a large grasp force.

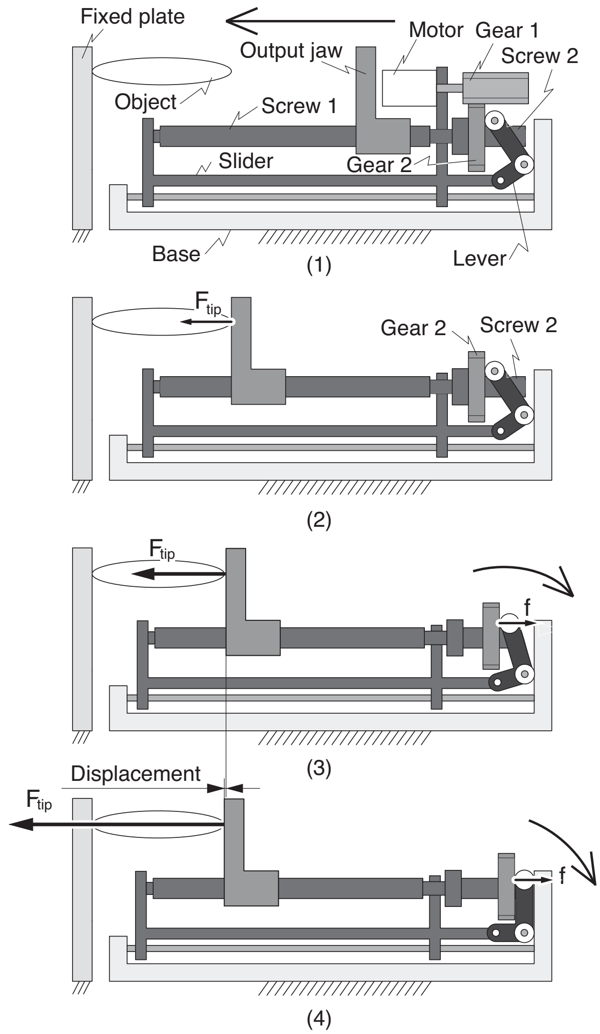

Fig. 2. Basic principle

Figure 3 illustrates the static forces in Fig. 2(3) and (4). We assume that all components are rigid bodies. The output jaw, screws 1 and 2 and the slider can be considered as a united rigid body, because they have no relative motion. The grasping force F_{tip} is equal to the reaction force acting on the lever from the base.

Let L_1 and L_2 be the perpendicular distances from joint (a) to rollers 1 and 2, respectively. f is the force gear 2 exerts to the lever. The moment balance equation is given by

$$F_{tip} = \frac{L_2}{L_1} f \tag{1}$$

Let α be the angle of the lever shown in Fig. 3. When the configuration of the lever reaches Fig. 2(2), $\alpha \rightarrow 0$ and $L_1 \rightarrow 0$. Theoretically, the grasping force F_{tip} becomes infinity. In practice, it is finite due to the elastic deformations of the components of the gripper and the grasped object. Nevertheless, a very large grasp force F_{tip} can be expected when their stiffness is enough large. This is the basic principle of the proposed mechanism. A gripper which grasps an object from both sides with two output jaws is shown in

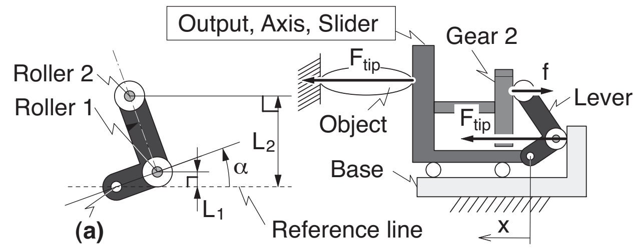

Fig. 3. Static forces

section V.

B. Details of the principle

Figure 4 shows more details of the mechanism. The lever is attached on the slider with the revolute joint (a). Springs 1 and 2 hold the lever in contact with the base and gear 2, respectively. The output jaw is attached on a nut on screw 1. Since the nut and output jaw are a united part, we mean the nut by the output jaw. Screw 2 is connected to screw 1 and they have a common screw shaft. Screw 1 has a larger pitch than screw 2, which enables quick motion of the output jaw. Gear 2 has outer and inner teeth, that is, its hub is a nut on screw 2. Since the nut and gear 2 are a united part, we mean the nut by gear 2. The stopper is attached on screw 2.

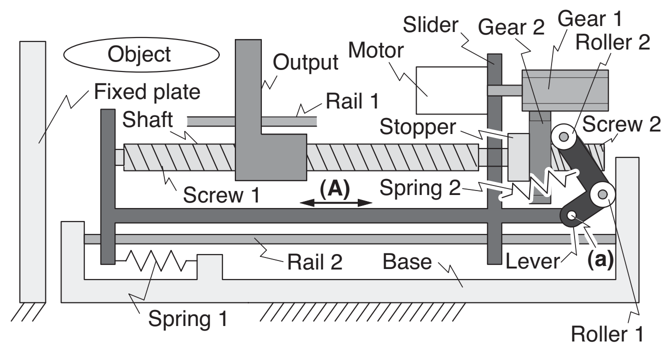

Fig. 4. Gripper with the grasp force magnifying mechanism

Screws 1 and 2 are right-handed[1]. Since they are fixed on the slider, rotation of screw 1 to the right/left moves the output jaw to the right/left, respectively (Fig. 5 (1) and (2)). We need to make the following assumption so that the motor can move the output jaw to the left with gear 2 in Fig. 5 (1).
Assumption 1: By rotating gear 2 to the left, screws 1 and 2 rotate together with gear 2 which remains fastened on the stopper.

Otherwise if gear 2 is not fastened securely, gear 2 would be loosened. Section II-D presents an initializing procedure to ensure Assumption 1. When the output jaw is constrained and screws 1and 2 do not rotate, rotation of gear 2 to the right/left moves itself to the left/right, respectively (Fig. 5 (3) and (4)).

[1]A right handed male screw advances with a right turn when its pair female screw is fixed

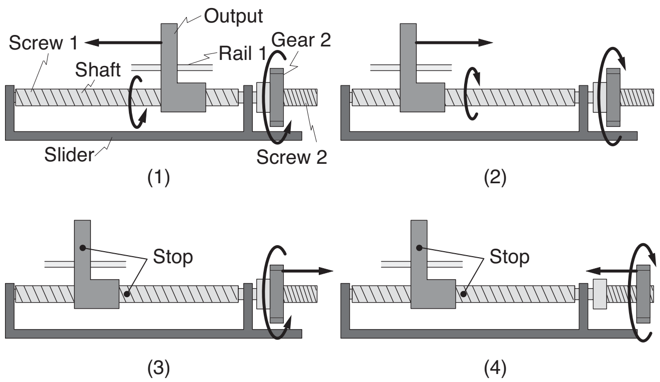

Fig. 5. Rotation of gear 2 and its resulting motions

Therefore, the motor rotates gear 2 to the left to grasp the object in Fig. 4. Rotating gear 2 to the right results in ungrasping. The following assumption is also necessary so that the output jaw maintains the grasp and gear 2 pushes the lever in Fig. 4 (2) through (4).

Assumption 2: Screws 1 and 2 are non-backdrivable, that is, they do not turn when a force is applied to the output jaw and gear 2, respectively.

The condition for non-backdrivability is shown next.

C. Mechanics of a screw

We review the mechanics of a screw[6]. A male screw can be regarded as a slope by unrolling it as shown in Fig. 6. A female screw can be regarded as an object on the slope. Let θ be the angle of the slope (lead angle), and ρ be the friction angle between the male and female screws. Let also $\tau_{\oplus}$ and $\tau_{\ominus}$ be the torques to tighten and loosen the female screw, respectively. Their relationship is given by:

$$\tau_{\ominus} = \frac{\tan(\rho - \theta)}{\tan(\rho + \theta)} \tau_{\oplus}. \quad (2)$$

Therefore, as θ increase, the torque $\tau_{\ominus}$ to loosen the female screw decreases even if the tightening torque $\tau_{\oplus}$ is the same. If $\rho < \theta$, $\tau_{\ominus}$ is negative, which means that the pair of male and female screws are backdrivable.

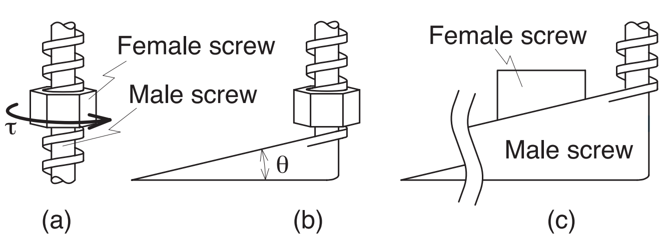

Fig. 6. Slope model of a screw

Let θ_1 and θ_2 be the lead angles of screws 1 and 2, respectively. Assume that the friction angle ρ of screws 1 and 2 are the same. We already assumed that $\theta_1 > \theta_2$ in Section II. Screws 1 and 2 must be non-backdrivable. Therefore

$$\rho > \theta_1 > \theta_2. \quad (3)$$

D. Initializing procedure

This section presents an initializing procedure to ensure Assumption 1. There are four contact states of gear 2 and the output jaw as shown in Fig. 7 (a)-(d).

(a): The output jaw and gear 2 are in contact with the slider and the stopper, respectively.

(b): None of them are in contact.

(c): Only the output jaw is in contact with the slider.

(d): Only gear 2 is in contact with the stopper.

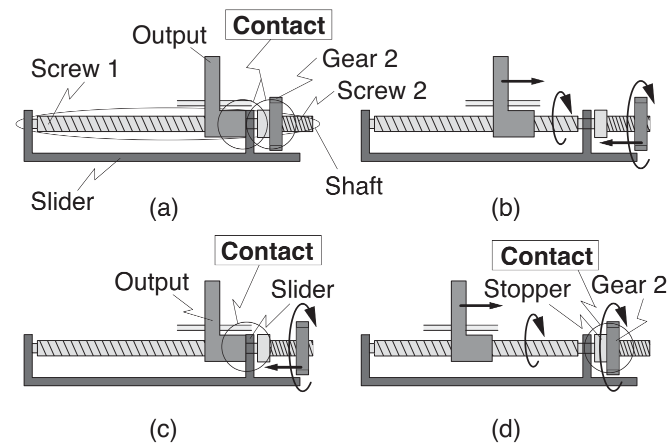

Fig. 7. Four contact states

(d) is the contact state in Fig. 2 (1). The following initializing procedure ensures Assumption 1, regardless of the initial contact state.

(1): Rotate gear 2 to the right, which results in contact state (a) from any other states.

(2): Continue to rotate gear 2 to the right to tighten gear 2 on the stopper and the output jaw on the slider, respectively.

(3): Rotate gear 2 to the left with a torque increased from zero. Then the output jaw is loosened first and it moves to the left.

Proof of procedure (1): In contact state (c), by rotating gear 2 to the right, screws 1 and 2 do not rotate since the output jaw is stopped by the slider. Therefore gear 2 moves to the left. Then it makes contact with the stopper, which is contact state (a). Similarly contact state (d) can be transferred to contact state (a). In contact state (b), by rotating gear 2 to the right, either the output jaw moves to the right or gear 2 moves to the left. The former case results in contact state (c) and the latter case contact state (d), respectively. They can be transferred to contact state (a).

Proof of procedure (3): Let $\tau_{\oplus}$ be the troque to tighten the output jaw and gear 2 in contact state (a), and $\tau_{1\ominus}$ and $\tau_{2\ominus}$ be the torques necessary to loosen the output jaw and gear 2, respectively. From Eq. (2), $\tau_{1\ominus}$ and $\tau_{2\ominus}$ are given by,

$$\tau_{1\ominus} = \frac{\tan(\rho - \theta_1)}{\tan(\rho + \theta_1)} \tau_{\oplus} \quad (4)$$

$$\tau_{2\ominus} = \frac{\tan(\rho - \theta_2)}{\tan(\rho + \theta_2)} \tau_{\oplus} \tag{5}$$

Since $\theta_1 > \theta_2$, $\tau_{1\ominus} < \tau_{2\ominus}$. Therefore the motor can loosen the output jaw first with a torque increased from zero. Then the output jaw starts to move to the left. Note that dynamical effects may loosen gear 2. We experimentally verified that our developed gripper could maintain gear 2 fastened on the stopper in the initializing procedure.

M3 (lead: 0.5 mm, $\theta_1 = 3.4$ deg) and M3 (lead: 0.35 mm, $\theta_2 = 2.3$ deg) are selected for screws 1 and 2, respectively. A general problem with screws is jamming. Section IV shows an extra procedure to recover from screw jamming.

III. EXPERIMENTS

A. Experimental setup

Figure 8 shows the developed parallel jaw gripper. To show its inside, its upper plate is removed in the upper photo. Its dimensions are $80 \times 25 \times 25$ mm and its mass is only 86 g. The motor is 1.2 W and weighs 15g. The number of teeth of gears 1 and 2 are 14 and 48, respectively. To measure the grasp force F_{tip}, a force sensor is installed in the fixed plate.

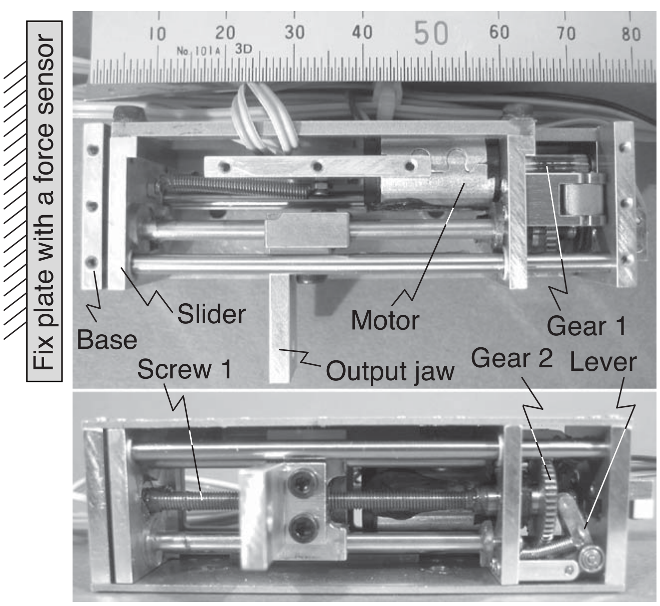

Fig. 8. The developed gripper

B. Tightening torque in the initializing procedure

The tightening torque $\tau_{\oplus}$ in the initializing procedure is determined experimentally. It is proportional to the motor current i. By varying it from 0.15, 0.27, 0.40 to 0.60[A], we checked whether or not screw jamming occurred. For each current, we repeated 100 times. When $i = 0.15$ and 0.27[A], screw jamming occurred only once. When $i = 0.40$ and 0.60[A], it occurred every time. Therefore we set the limitation value of the motor current i 0.15[A].

C. Grasping

We measured the grasp force F_{tip} and the current i when the developed gripper grasped an object without screw jamming. Figure 9 shows the experimental result, and Fig. 10 the snapshots of the experiment. Numbers in Fig. 9 correspond to those in Fig. 10. (1) and (2) are the initializing procedure.
(1): The output jaw was moved to the right by rotating gear 2 to the right.
(2): The output jaw and gear 2 were tightened.
(3): The output jaw was moved to the object by rotating gear 2 to the left.
(4): The output jaw made contact with the object, and gear 2 was loosened from the stopper and pushes the lever.
(5): The grasp force F_{tip} exceeded more than 200 N as shown Fig. 9 (b).

It was verified that Assumption 1 held, that is, gear 2 remained fastened on the stopper in (3). Because the proposed mechanism uses non-backdrivable screws, the grasp force remain large even if the motor current is off, which is an advantage of this mechanism.

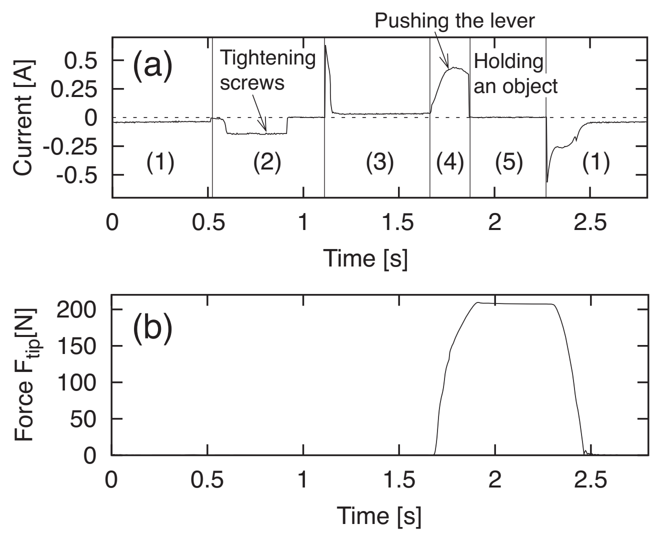

Fig. 9. Experimental results of current i and fingertip force F_{tip}

We verified that the gripper could grasp objects of different sizes with a large grasp force. The gripper grasped objects of 13 different sizes in length ranging from 22.3mm to 40.3mm by 1.5mm, and the grasp force was measured 20 times. Fig. 11 shows the experimental results. The average of the grasp forces F_{tip} was 194 N.

For comparison, the gripper grasped an object only using the screw 1 without the force magnifying mechanism. When the grasp force F_{tip} was smaller than 60 N, it could grasp and ungrasp an object smoothly without screw jamming. When the grasp force exceeded 65 N with a large motor current, the screws were jammed with 20% frequency even if enough machine lubricant was supplied to the screws. Therefore, the maximum grasp force without the force magnifying

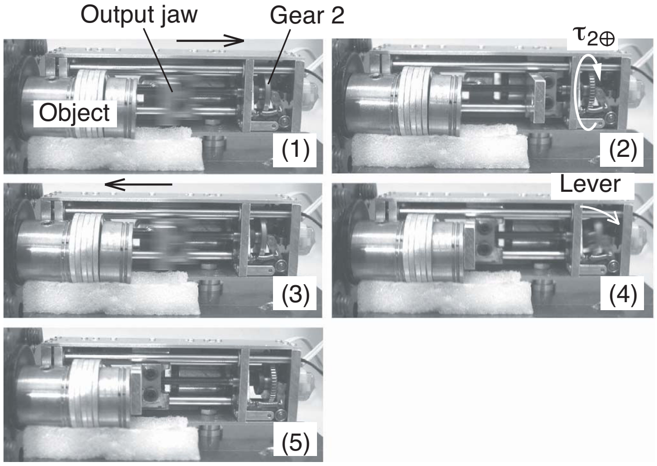

Fig. 10. Snapshots of the experiment

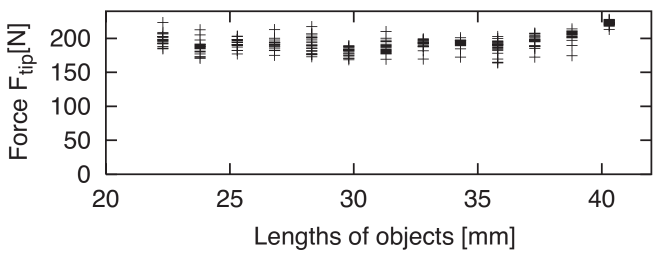

Fig. 11. Experimental results of fingertip forces F_{tip} versus the lengths of objects (22.3 - 40.3 mm)

mechanism was 60 N. The force magnifying mechanism can exert a grasp force three times as large as that without it.

IV. Screw jamming

A. Recovery procedure

In our experiments screw jamming occurred when gear 2 was tightened on the stopper with an excessive tightening torque or with insufficient machine lubricant. The output jaw was rarely jammed. This section shows an extra procedure to recover from screw jamming. To invoke such an extra procedure, the gripper needs to recognize the occurrence of screw jamming. If the motor is driven by a constant voltage V, the motor current i becomes larger when it is stopped than when it is rotating. When the gripper runs normally without screw jamming, the current i exceed 0.5 A only shortly as shown in Fig. 9. Therefore when the current exceed $i_t = 0.5$ A for longer than $t = 1.0$ s, the gripper recognizes screw jamming.

To loosen the jammed screw, we propose the following procedure. First, the motor slowly rotates gear 1 a little in the reverse direction with a stepwise voltage V_a for the period t_a as shown in Fig. 12 (c). This can make a gap as shown in (a). Next, the motor rotates gear 1 with a pulsive voltage V_b for the period t_b so that the tooth of gear 1 impacts on that of gear 2 as shown in Fig. 12 (b). The pulsive voltage is applied repeatedly until the screw is loosened. The values V_a, V_b, t_a and t_b are determined experimentally.

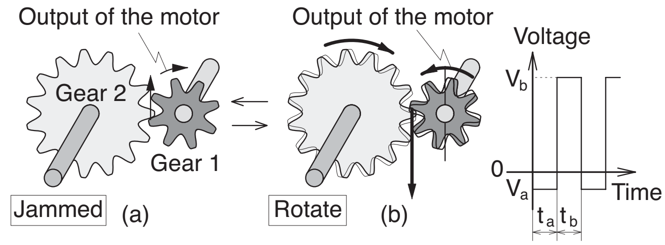

Fig. 12. Extra procedure to loosen a jammed screw

B. Test of the recovery procedure

In section III-B, gear 2 is jammed every time when the motor current is $i = 0.40$ and 0.60 A. To make gear 2 jammed intentionally, we tightened gear 2 with $i = 0.40$ and 0.60 A, tested the recovery procedure 100 times for each current. Every time, the gripper could recognize the occurrence of screw jamming and the procedure could loosen gear 2. Figure 13 shows the number of pulses necessary to loosen gear 2. When $i = 0.40$ and 0.60 A, the average number of pulses are 4.6 and 14.6, respectively.

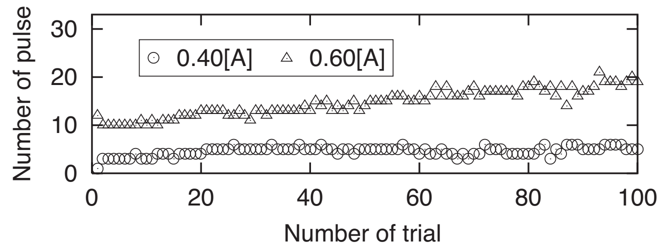

Fig. 13. Number of pulses necessary to loosen gear 2

C. Frequency of screw jamming

We examined how frequently screw jamming occurred when the gripper grasped an object with the normal current $i = 0.15$ A. This test was repeated 5000 times. Before the experiment, machine lubricant was supplied to the screws. Figure 14 (a) shows the grasp force F_{tip}. The symbol $\times$ is plotted when the gripper recognizes screw jamming. Figure 14 (b) shows the number of the pulses necessary to loosen the jammed screw.

From about 1500 to 4500 times, no screw jamming occurred and the grasp force reached its maximum, 200 N. The gripper worked most smoothly. This is because the machine lubricant was in the best condition. After 4500 times, screw jamming occurred 105 times, and the grasp force decreased when it occurred. Table I shows the average of the grasp force F_{tip} and the number of occurrence of screw jamming every $1,000$ times. After 5000 times, machine lubricant was supplied again. Next 1000 times, screw jamming occurred only once. The experimental results show that screw jamming does not occur when machine lubricant is in the good condition.

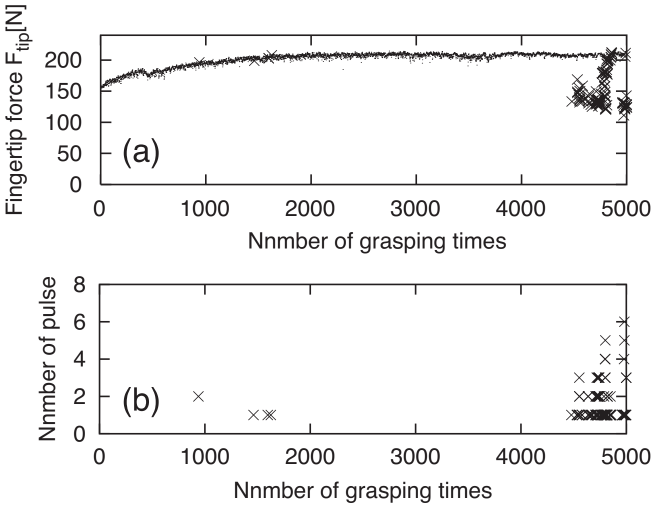

Fig. 14. Experimental results of repeated grasping test

TABLE I

FREQUENCY OF SCREW JAMMING AND FINGERTIP FORCE

Grasping times	Fingertip force [N]	Jammed
1-1000	180	1
1001-2000	202	4
2001-3000	208	0
3001-4000	208	0
4001-5000	202	105

V. DISCUSSION

Finally we discuss a parallel jaw gripper that grasps an object from both sides by two output jaws with the proposed force magnifying mechanism. Figure 15 shows a mechanism of such a gripper. The right half is same as that shown in Fig. 4. Shafts 1 and 2 are connected by a coupling as shown in Fig. 16. This allows shaft 1 to move in the direction of (A) freely while transmitting a torque to shaft 2. Screw $1'$ is left-handed so that output jaws 1 and 2 can open and close in the opposite directions to each other.

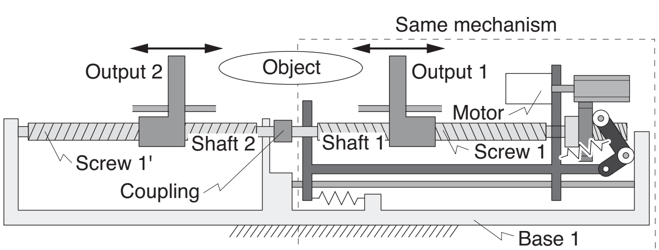

Fig. 15. A parallel jaw gripper with two output jaws

When grasping an object, either output jaw 1 or 2 touches it first. In either case, we assume that the two output jaws 1 and 2 make contact with the object finally. This assumption holds if the manipulator on which the gripper is installed is compliant with a contact force, by compliance control, impedance control, etc. Then Shafts 1 and 2 stop, and output jaw 2 also stops. Output jaw 2 works as the fixed plate in Fig. 4. The lever pushes output jaw 1 to the left similarly as the gripper in Fig. 4. Output jaw 1 can shift because of the coupling. Therefore, this mechanism can generate a large grasp force as well.

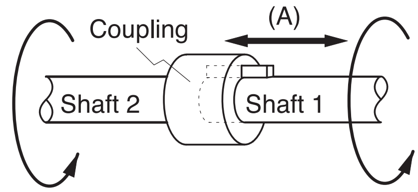

Fig. 16. Coupling between shafts 1 and 2

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