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A Two-Phase Gripper to Reorient and Grasp

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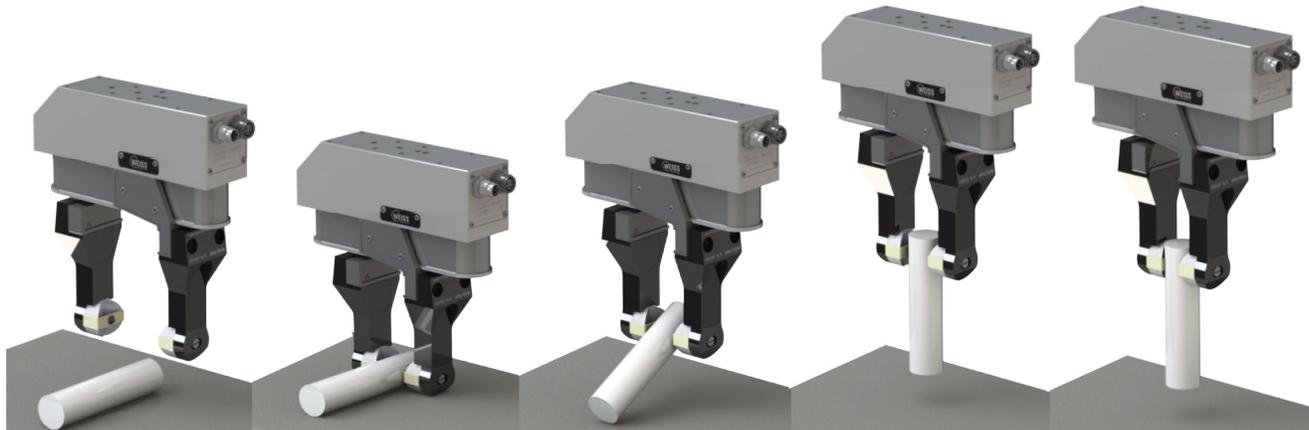
Abstract— **This paper introduces the design of novel two-phase fingers to passively reorient objects while picking them up. Two-phase refers to a change in the finger-object contact geometry, from a free spinning point contact to a firm multi-point contact, as the gripping force increases. We exploit the two *phases* to passively reorient prismatic objects from a horizontal resting pose to an upright secure grasp. This problem is particularly relevant to industrial assembly applications where parts often are presented lying on trays or conveyor belts and need to be assembled vertically.**

Each two-phase finger is composed of a small hard contact point attached to an elastic strip mounted over a V-groove cavity. When grasped between two parallel fingers with low gripping force, the object pivots about the axis between the contact points on the strips, and aligns upright with gravity. A subsequent increase in the gripping force makes the elastic strips recede into the cavities letting the part seat in the V-grooves to secure the grasp. The design is compatible with any type of parallel-jaw gripper, and can be reconfigured to specific objects by changing the geometry of the cavity. The two-phase gripper provides robots with the capability to accurately position and manipulate parts, reducing the need for dedicated part feeders or time-demanding regrasp procedures.

I. INTRODUCTION

Robotic research has long been interested in the ability to grasp and manipulate a large and varied set of objects. Due to stringent requirements on speed, precision, and reliability, the automation industry however has preferred simple gripping solutions that can accurately localize and securely grasp a small set of objects [1]. Furthermore, the need for object manipulation at assembly is often bypassed by specialized part feeders which present the parts in a pose suitable for picking and use.

We present a novel design of two-phase fingers which alleviate the need of part feeders by grasping and passively reorienting a set of parts. Two-phase refers to a discrete change in the contact geometry between fingers and part as the gripping force increases, where the gripper function switches from passive reorientation of the part to a secure grasp. In particular, this paper focuses on grasping and reorienting cylindrical or prismatic parts, a very frequent geometries in industrial assembly settings [2]. We demonstrate how the two-phase gripper reorients cylindrical parts to an upright pose and grasp them securely in an uninterrupted and continuous motion.

Figure 1 illustrates the two-phase finger in action. The design is composed of a small contact point on an elastic strip mounted over a V-groove cavity. When an object is grasped with low gripping force, it pivots about the contact points on the strips until it aligns with gravity. As the gripping force increases, the elastic strips recede into the cavities, and the object sits into the V-grooves securing the grasp.

We demonstrate the design by instrumenting two commercially available grippers (2-Finger 85 from Robotiq, and WSG32 from Weiss Robotics) and testing them with three different object types. The experiments validate the effectiveness of the design in reorienting and securing the parts.

The passivity of the reorientation of the part makes the two-phase fingers compatible with most grippers. By changing the geometry of the cavity in the fingers, the two-phase fingers can be optimized for different parts. Modular and configurable solutions for picking and reorienting parts have the potential to make assembly automation faster, flexible, and reliable.

II. RELATED WORK

Humans use regrasps, in all of their flavors, as an integral part of day-to-day manipulation activities. Empowering robots with such dexterity has been an inspiration for roboticists for years. In particular, under the assumption of sufficient gripper dexterity and the ability to finely control the motions and forces at their fingertips, manipulation research has led to planning algorithms and demonstrations of in-hand object reorientation. The approach, which banks on the concept of "dexterous hands" [3, 4], allows the gripper to slide or roll its fingers over the object and/or make and break finger contacts whenever required [5, 6, 7, 8, 9]. This approach addresses the general challenge of in-hand manipulation and is able to generate simulated object reorientation strategies. In practice, however, it suffers from limitations such as high design and control complexity and small motion range.

A parallel more relevant approach is the focus on particular types of object reorientations with specially designed hardware or manipulation primitives. Nilsson [10] demonstrated application of pushing and squeezing to reorient the objects and to localize them. Erdmann and Mason [11] proposed a sensor-less tray capable of reorienting parts by tilting. Goldberg [12] studied the orientation a planar part by a series of squeezes with a parallel-jaw gripper, and Lynch and Mason [13] demonstrated the stability and controllability of an pushed planar object.

In fact, within the context of industrial assembly, full dexterity however is often not necessary. In practice, thanks to engineered environments, a small set of regrasps dominate most of the manipulation required for assembly operations. *Pivoting*—rotating an object about the axis determined by two finger contacts—is a prominent one, recognized and studied in the past. Rao et al. [14] explored its effectiveness for part reorientation for assembly automation. Their work exploits gravity to reorient grasped objects, as we do in this paper and as we previously explored as a form of "extrinsic dexterity" [15]. Holladay et al. [16] further propose a general framework for pivoting with dynamic arm motions. In more recent work, we studied and modeled the frictional interaction between a gripper and an object for pivoting motions produced by pushing a grasped object against the environment.

In all these examples pivoting is achieved by exploiting the minimal frictional resistance offered by the small, ideally point, contacts the fingers make with the object. For passive pivoting, we want low frictional torque to let the object reorient under the effect of gravity or dynamic motions, but we also need high friction to maintain the new orientation

once reached. In this paper, we propose a two-phase mechanism capable of providing a change in contact geometry to alternatively satisfy both goals.

Contact geometry between gripper and object determines in great part the object's mobility. The relationship is well understood and has been extensively exploited for the design of fixtures and mechanisms to either positively locate an object, or move it along a trajectory. The application of selective kinematic contact constraints is the basis for the synthesis of fixtures [17, 18], exact-constraint design [19], and the concept of form-closure grasping [20], widely applied to robot manipulation planning and to the design of robot hands and fingers. In the 19th century, Reuleaux [21] developed a sophisticated approach for the kinematic analysis of contacts. Recently Rodriguez and Mason [22] presented a mathematical framework for designing effector shape for a task given as a set of contact constraints, such as grasping a set of objects or moving them.

The developed two-phase gripper incorporates two different operating modes—pivoting and firm grasping—by exploiting the kinematic and frictional constraints offered by two different contact types. Section III motivates the design of the two-phase gripper. Section IV describes its design in detail, and Section V analyzes the mechanics of its working principle. In Section VI we provides observations and insights from experimental testing with different grippers and objects, and finally Section VII summarizes the contributions.

III. PROBLEM MOTIVATION

Robotics research has been driven, and is still driven in part today, by the needs of factory automation. The last two decades have seen a remarkable evolution of robotic manipulators leading to precisions of 30 microns, speeds of a few meters per second, the availability of force feedback and force control, as well as safety and compliance. Unfortunately, the lack of robust solutions for object manipulation has limited the role of these remarkable machines to mostly pick-and-place.

Getting an object in a fitting pose for an assembly, either by picking it up in the required pose or by regrasping it, is crucial for the success of the assembly. Often, the approach practiced in industry is to avoid the need for regrasping. An ancillary system deals with part feeding by singulating and locating a parts from a pile by passing them through specially designed pathways that reorient them and present them to the robot in an already suitable pose. This approach, although proven robust, incurs on important space, time, and set-up requirements, leading to huge costs in the set up of a new assembly line. When the product changes, little of the set-up can be reused. These factors discourage the possibility of assembly automation for products with short upgrade cycle time.

The large market for automation of electronic product assembly and the demand from small scale industries for affordable automation are two major contributors to the rising interest in *flexible automation*. It aims for automation systems
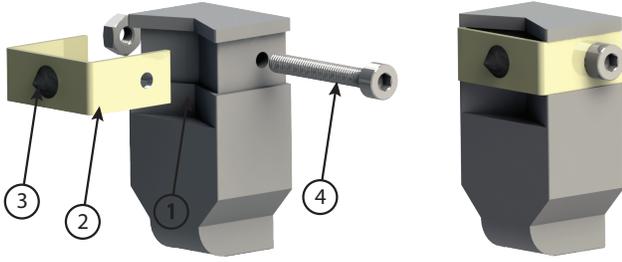
Fig. 1. Components of a two-phase finger: 1) V-groove cavity, 2) Elastic strip, 3) Point contact, and 4) Fastener. The assembled finger is shown on the right.

Fig. 2. Schematic of the change in contact geometry at the two-phase fingers as the grasping force switches from low (left) to high (right).

that are modular, easy to set up and adapt, and easy to integrate among human co-workers [23, 24]. Dexterity has been identified as one of the major roadblocks and essential capabilities needed to address the challenges in next-generation automation [25]. Rather than general-purpose dexterity, we explore a solution to perform a particular reorientation precisely and reliably, and with the ability to be easily adaptable to other parts and systems with minimal reconfiguration.

In this paper we focus on a particular case commonly encountered in assembly operations - reorienting cylindrical parts from a horizontal pose on a table or a conveyor belt to an upright pose required for assembly. We focus on cylindrical parts which are one of the most common geometries within industrial assembly, with the goal of providing a reliable and fast method for picking, reorienting and securing.

The functional requirements of the gripper are as follow:
1) Passive reorientation of a cylindrical object from a horizontal pose to an upright pose.
2) Secure the grasp on the object in the new upright orientation.

The following section details the design.

IV. TWO-PHASE GRIPPER

The motion of a grasped object is governed by the kinematic and frictional properties of all contacts it makes. To let an object pivot under gravitational force, contacts must offer minimal frictional torque, characteristic of contacts with small area. On the other hand, to localize and to hold the object securely after it pivots, specific kinematic constraints and significant frictional resistance needs to be provided. The proposed design aims to fit both needs.

A. Design Features

We rely on a built-in mechanism in the fingertips to change the finger-object contact geometry from point contact with low-friction to multi-point contact with high friction. The change on the contact geometry is triggered by the magnitude of the gripping force. The functionality is depicted in Figure 2.

Figure 1 shows the design of the two-phase finger that can be retrofitted to any common parallel-jaw gripper. The finger has three major components:
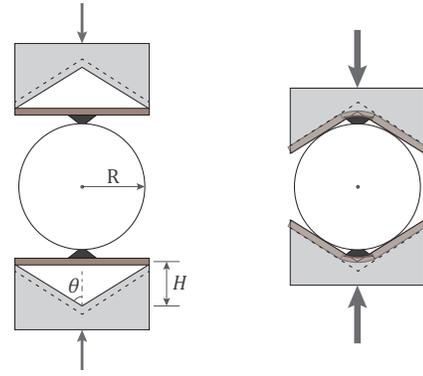
1) A cavity to localize and hold objects.
2) An elastic strip running over the cavity.
3) A point contact on the strip .

We describe each component in more detail.

V-groove cavity: The cavity is meant to provide kinematic constraints that force the object to align to an upright pose, and later maintain that pose even when the robot or hand is freely moved around.

This paper focuses on cylindrical objects, and consequently a canonical V-groove gives an appropriate geometry for the cavity. Given the radius R of the cylinder to pick, we chose the values for the depth of the cavity H and its angle 2θ so that the fingers will not touch each other when holding the object. Otherwise the object would be able to move even with the gripper fully closed. We impose then:

$$H \leq R/\sin\theta \tag{1}$$

As illustrated in Figure 3, the expectation is that the kinematic constraints offered by the V-grooves will push the cylindrical object to the center of the cavity and make it vertical from anywhere within the groove. After the alignment, and when combined with friction from contacts within the V-groove, we get a force-closure grasp on the object [26].

Elastic strip: The role of the elastic strip is to facilitate the transition from a point contact to patch contact as the gripping force increases. At low gripping force, we would like the elastic strip to provide high stiffness to maintain a point contact between fingers and object, and low stiffness as the gripping force increases above certain threshold so that the strip recedes into the cavity and allows surface contact between the finger and the object. However, practically achieving such "softening spring" behavior can be involved.

For the purpose of prototyping, we used a rubber band with a preload as the elastic strip. The required stiffness value for the elastic strip is bounded by two constraints based on the desired application.

Let δ_{pivot} be a maximum allowable deflection in the strip for the gripping force suitable for pivoting the object F_{pivot} (estimation of F_{pivot} is discussed in section (V)). This gives

(a) Top-view of an object in the cavity

(b) Side-view of an object in the cavity
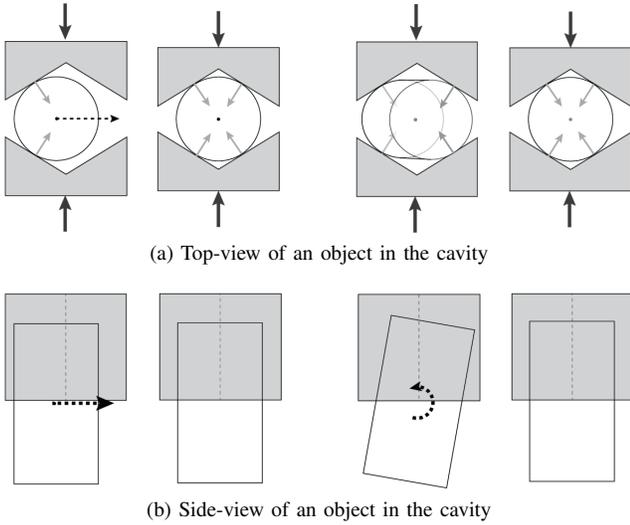
Fig. 3. Localization effect of V-groove cavity. Localization of a cylindrical object when offset in linear sense is shown on left, while that in angular sense is shown on right.

a low bound on the stiffness of the strip (K).

$$K \geq F_{\text{pivot}}/2\delta_{\text{pivot}} \tag{2}$$

Similarly, let δ_{grasp} be the minimum deflection needed in the strip when the object is held in the V-groove cavities giving an upper bound on the stiffness of the strip.

$$K \leq F_{\text{grasp}}/2\delta_{\text{grasp}} \tag{3}$$

where $\delta_{\text{grasp}} = 2H\frac{(1-\sin\theta)}{\cos\theta}$ is the minimum extension needed in the strip so that it can recede and sit in the cavity and F_{grasp} is the high gripping force applied for grasping the object. F_{grasp} is limited by the maximum grasping force the gripper can apply.

We will proceed under the assumption that as long as the stiffness of the strip satisfies (2) and (3), the variation in the stiffness does not affect the functionality of the gripper, and that the stiffness of the strip remains constant throughout the operation.

Point contact: The role of the point contact on the elastic strip is to act as a hinge to support and allow minimal frictional resistance to the rotation of the object in fingers under gravity. Though ideally we want point contacts between the object and the fingers for pivoting, in reality they are patch contacts with small area.

In Section V-B, we further discuss the consequences of having small area contacts rather than idealized point contacts on the estimation of F_{pivot}.

B. Operational Procedure

In this section we explain a typical operation for the two-phase gripper. The complete manipulation task can be broken down into the following steps:

1. The two-phase gripper reaches over a cylindrical object lying on a flat surface with its longitudinal axis horizontal.
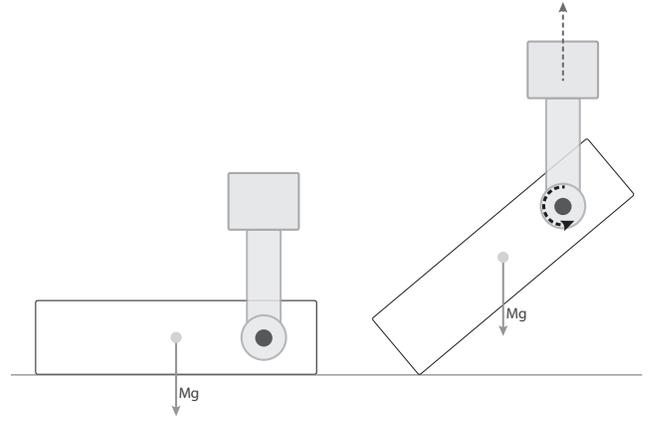

Fig. 4. Schematic of the pivoting phase. (left) The two-phase gripper holds an object offset from the center of gravity and (right) lifts it making it pivot about the fingertips. The bold arrow indicates the rotation of the object from the hand point of view.

2. The fingers hold the object offset from the center of mass with a low gripping force, just sufficient to prevent the object from slipping.
3. The object is raised, while it pivots about the axis between the finger contacts, until it is completely lifted from the surface and aligned upright in the gripper.
4. The grip on the object is tightened, which passively shifts the cylinder to the center of the cavity and secures the grasp.

V. MECHANICS OF PIVOTING

In this section we analyze the mechanics of the pivoting manipulation and the criterion to select an appropriate value for the gripping force. Figure 4 shows the schematic of a cylinder being grasped and lifted.

The gripping force plays a key role in determining the success of the pivoting operation. It must suffice to prevent slipping of object, but needs to be small enough to allow pivoting under gravity. In order to lift the object without slipping, the linear frictional force at the finger contacts must balance the gravitational force. This determines a lower bound on the gripping force during the pivoting phase:

$$F_{\text{pivot}} \geq Mg/\mu \tag{4}$$

where M is the mass of the object, g is the gravitational acceleration and μ is the linear coefficient of friction at the finger contacts.

The upper bound on F_{pivot} is determined by the limit on the frictional resistance to allow pivoting, which to large extent is determined by the size of the contact area between the part and fingers. Following, we compare two different approaches to estimate the upper bound, first with idealized point contacts and second with more realistic small patch contacts.

A. Pivoting with point contacts

An idealized point contact with friction can transmit forces along three linear dimensions, one along the contact normal
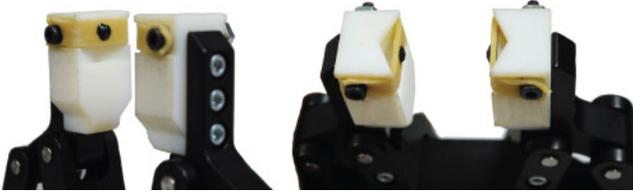
(a) Two-phase fingers mounted on a gripper
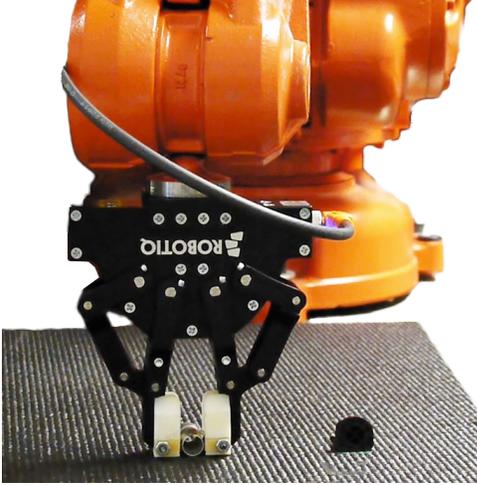
(b) Experimental Setup

Fig. 5. Prototypes of two-phase fingers are mounted on a gripper (top). Experimental setup showing different parts and the two-phase gripper mounted on a robot (bottom)

and two along the contact plane. In the ideal case, it does not offer any torsional resistance at contact [26].

This means that, as long as there is an offset between the center of gravity (CG) of the object and the finger contact locations, for any positive value of the gripping force, the object is free to pivot about the fingertips under the effect of gravity. Effectively, there is no upper bound on F_{pivot}.

B. Pivoting with small patch contacts

In practice, it is hardly possible to get point contacts. There is always a finite surface area at contacts that can provide some degree of torsional resistance.

We assume those contacts to be planar patches. A planar contact with friction can transmit a torque about the contact normal in addition to the forces along three directions as in the previous case. That torque, specially when an object is picked close to the center of gravity with high force, can counterbalance the gravitational torque and prevent the part from pivoting, which can cause problems.

The simplest approximation to capture torsional friction is to model a patch contact as a point contact that transmits a torque about that point with a certain torsional coefficient of friction (μ_{tors}), producing the frictional toque $\mu_{\text{tors}}F_{\text{pivot}}$. This model is often known as *soft contact model* [26]. However, estimation of μ_{tors} is not trivial and in general depends on the contact geometry, so needs to be updated when the contact geometry changes.

There are more involved ways to model patch contacts. A

model commonly used in manipulation planning is the *limit surface model* [27]. There are other models that are based on finite element approximations [28] which do not assume explicit knowledge of the torsional friction coefficient.

The focus of this paper is in the mechanical design of the two-phase fingers, and for the sake of simplicity, we will assume contacts to be circular, and finitely approximate them as a rigid set of point contacts forming a polygon concentric with the circular patch. The total frictional torque on the object can then be approximated as:

$$\tau_{\text{fric}} = \mu r F_{\text{grip}} \tag{5}$$

where F_{grip} is the gripping force and r is the radius of the circular patch contact.

For an object to rotate in the fingers, the frictional torque created at the finger contacts must be smaller than the moment created by the gravitational force on the object, $\tau_{\text{fric}} \leq MgL\cos\phi$, which sets an upper bound on the gripping force:

$$F_{\text{pivot}} \leq MgL\cos\phi/\mu r \tag{6}$$

where L is a moment arm, the offset between the CG of the object and the fingertip location, and ϕ is the angle between the axis of the cylinder and the horizontal plane. ϕ changes from $0°$ to $90°$ as the object pivots from the horizontal pose to the upright pose. Though the moment arm reduces as the object slowly pivots, the inertia gained by the object can help it to pivot as the the moment approaches zero. So, we only check if the following constraint holds true when the part is in the horizontal configuration:

$$F_{\text{pivot}} \leq MgL/\mu r \tag{7}$$

In summary, constraints $(1) - (7)$ collectively define the geometry of the V-groove cavity, stiffness of the elastic strip over it and the limits on the gripping force to pivot the object about the finger contacts.

VI. EXPERIMENTS AND CHARACTERIZATION

In this section we discuss the experimental validation of the effectiveness of the two-phase fingers. In particular we focus on the validation of the small patch models for the finger contacts and the effect of changes in the grasping location on the required gripping force for pivoting.

A. Experimental Setup and Procedure

For prototyping, we used 3D printed fingers with a V-groove cavity, and a rubber band with preload for the elastic strip. The point contact on the strip is made by placing a drop of liquid rubber on the strip and then curing it. The elastic strip is held in place using a cap screw.

We attached these fingers to two different grippers: Weiss Robotics WSG-32, with force feedback and force control, and the Robotiq 2-Finger 85 without force control. Both the grippers were mounted on an ABB IRB 140 industrial manipulator. We chose three different cylinders with different diameters and materials and one with a square flange, as our test objects.
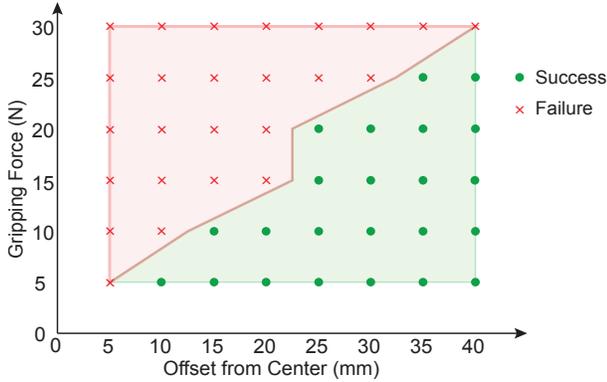
Fig. 6. Successful and failed pivoting experiments. The boundary between the regions is drawn for visualization purposes.

Fig. 7. The expected successful pivoting region is bounder by the two dotted lines, which represent (4) and (7). Th experimental results (colored regions) match well to the expectation.

Figure 5-b shows a typical experimental setup with two of the test objects, the two-phase gripper and the manipulator. For every experimental trial, we lifted the object from the ground with a low gripping force in a range suitable for pivoting the object and then grasped it tightly after it is fully lifted from the ground. The attempt is counted as success if the part is reoriented to an upright pose without slipping and securely held in the the V-groove at the end of the procedure. We conducted this experiment for multiple gripping force, and at multiple gripping locations along the length of the cylinder, for all the tested object. Figure 6 shows the results of those experiments for one of the objects, and for comparison, Figure 7 shows our expectation from the discussed pivoting models. We further detail the results in the following sections.

B. Experimental observations

Here we list the main observations made from the experimental trials:

1) The two-phase gripper successfully pivots all the tested objects to the upright pose, including a cylinder with flange, when lifted from the flange end.
2) The V-groove cavity is effective at eliminating a small deviation the object may have, either in linear or angular direction, from the perfectly upright pose. It localizes the cylindrical objects at the center of the cavity, which ensures a secure grasp.
3) The V-groove cavity does not work well with non-cylindrical shaped parts, such as squares. The geometry of the cavity would need to be re-designed for objects of different shapes.
4) The magnitude of the gripping force during the pivoting phase is crucial for success. The analysis allows us to bound the range of working forces with the constraints (4) and (7), which are validated by the experiments. A force controlled gripper can then simply close to a desired gripping force and control the pivoting operation. A position-controlled gripper with some form of in-series compliance can also execute pivoting, but requires more fine-tuning.
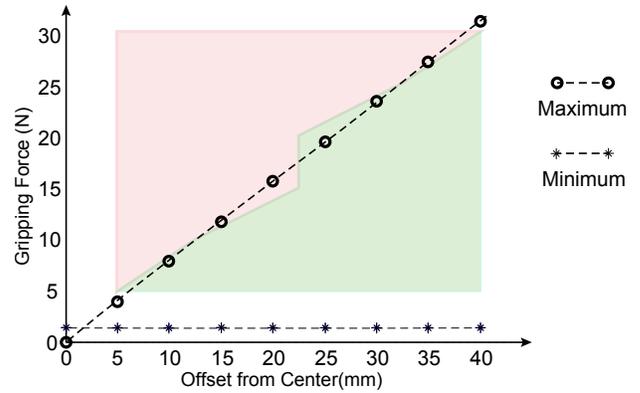
C. Experimental Validation of Predictions for Pivoting Success

As discussed in Section V-B, we approximate the contacts between an object and the fingertips by small patch contacts which offer small but non-negligible frictional torque about the contact normal. To let the object pivot between contacts, the gripping force must satisfy constraint (7),

As we pick an object farther away from its center of gravity, the moment arm L increases making the range of compatible gripping forces for pivoting bigger.

We conducted series of experiments of picking up a cylindrical object at varying offset distances from the center with different gripping forces. Figure 6 shows the outcome of the experimental trials. The run is counted as success if the object pivoted under gravity without slipping, and failure otherwise. Due to the limitations of the gripper used, we limited the range for the gripping forces to the region $5N - 30N$. The figure shows the increase in the valid gripping force region as the object is grasped farther away from the center.

Figure 7 shows the estimation of the limits on the gripping force found analytically for successful execution of pivoting. The analytical model used here assumes circular patch contacts of 3 mm diameter at the fingertips, which give a good match for the fingers used. To evaluate the coefficient of friction between the object and the fingers, we made rigid fingers with the same rubber material at the tips. We picked the desired object and attempted to push it linearly in the grasp. Based on the gripping force and pushing force data generated from multiple experiments the linear coefficient of friction for the finger-object pair is estimated to be 0.6.

Following the 'no slip' criterion governing the minimum force at the fingers (4) and 'minimal torsional resistance' criterion governing the maximum force (7), we calculated the bounds on the gripping force which are shown in Figure 7. They are overlapped with the regions of success and failure trials observed during the experiments. Close resemblance of analytical and experimental results show that, given the mass of the object and the coefficient of friction between

the fingers and the object, we can model the process well enough to predict the gripping force required to successfully operate the two-phase gripper.

VII. DISCUSSION

This paper presents the design of a *two-phase gripper*, composed of a standard parallel-jaw gripper instrumented with special fingers capable of passively reorienting and securely holding a set of objects. The contact geometry between the fingers and the object changes from a point contact, which allows reorientation through pivoting, to a multi-point contact, which secures the grasp in the new orientation, as the gripping force increases. We focus on the application of the two-phase gripper to reorientation of cylindrical objects from horizontal to upright pose and then securely grasping them.

The two-phase fingers can be retrofitted to any parallel-jaw gripper of an appropriate size, and are composed of three main elements: a V-groove cavity, an elastic strip over the cavity and a point contact on the strip. We manufactured the fingers and tested them with two different industrial grippers for manipulating different cylindrical objects. When grasped between the fingers with low gripping force, a cylindrical object pivots about the small contacts on the strips under the effect of gravity and aligns upright in the fingers. The grasp on the object is then tightened so that the elastic strips recede into the cavities and the object is localized and securely held in the V-groove cavities in the fingers.

The idea of two-phase fingers can be easily extended to different shapes of objects by reconfiguring the cavity in the fingers. An algorithmic design of it based on the object shape is an interesting research topic we are further exploring.

The two-phase gripper is a demonstration of mechanical intelligence embedded in the design of the phalanges and its potential to facilitate dexterous manipulation of objects with simple, commonplace industrial grippers. Such modular, easily reconfigurable, and easy to fabricate features have the potential to add flexibility and reliability to assembly automation.

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