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# A Robotic Mechanism for Grasping Sacks

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***Abstract*—This paper describes a novel robotic end-effector and a method for grasping deformable objects with undefined shapes and geometry, such as sacks and bags. The first prototype end-effector, designed for applications in the U.S. Postal Service, is comprised of two parallel rollers with gripping surfaces in which the rollers are pushed toward each other. When the end-effector comes into contact with any portion of the deformable object, the rollers turn inwardly so that a graspable portion of the object is dragged between the rollers. The rollers stop rotating when a graspable portion of the material/object is caught in between, allowing the object to be maneuvered by the robot. The object is released when the rollers turn outwardly. The end-effector described in this article can grab and hold filled sacks from any point on the sack, regardless of the sack's orientation. Experimental evaluation of the end-effector has proven the design and implementation remarkably effective. This article describes the hardware, control method, and design issues associated with the end-effector.**

***Note to Practitioners*—Delivery and postal services around the world currently use sacks to hold letters, magazines, and small boxes. The considerable weight of these sacks, their lack of handles, eyelets, or other operator interfaces, and the unpredictable shape and size of the packages within create awkward and uncomfortable handling predicaments for mail handlers at all U.S.Postal Service distribution centers. Currently, no robotic hand or end-effector is commercially available to grab and hold sacks effectively, so sacks must be handled manually by postal employees in distribution centers. This paper describes the design of a novel robotic end-effector for manipulating deformable objects with undefined shapes, such as sacks and bags. This device, which does not mimic human hand architecture, is simple and practical; it makes use of the friction between two rotating rollers to grab sack material when it is in close proximity of the end-effector. The rollers cease rotation when sufficient sack material is collected between the rollers to support the sack. They reverse their rotation, and turn outwardly to release the sack again. This end-effector is able to grab a sack at any point, does not require the edge of the sack to be gathered and flattened prior to grasp, does not require the sack to be placed on its bottom, needs no operator intervention, does not use the weight of the sack to lock and secure the sack in the end-effector, and does not damage the sack contents.**

***Index Terms*—Compliant, end-effector, grasp, robotics, rollers, sacks.**

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## I. Introduction

POSTAL services across the world use sacks to hold letters, magazines, and small boxes. These sacks, handled manually by mail handlers, are often filled to 70 lbs in weight with magazine bundles, envelopes, and parcels. For mail handlers, the key contributing factors to awkward and uncomfortable manual handling processes are:

- the considerable weight of the sacks;
- the lack of handles, eyelets or other helpful operator interfaces on the sacks and parcels;
- inconsistency in shape, size, and weight of the sacks in a workstation.

During repetitive pick-and-place maneuvers, the above factors have shown to lead to increased risk of wrist, finger, and back injuries among mail handlers. To lower the risk of injuries and to expedite mail processing, the U.S. Postal Service (USPS) has employed various robotic devices to automate some of its mail handling activities. This paper describes an end-effector that is designed to work with these robotic systems to grab and hold sacks. To understand the end-effector requirements, several USPS distribution centers were extensively studied. The following two sack-handling situations were identified to benefit most from robotic assistance, and were hence thoroughly analyzed by the authors in the design of the end-effector described here.

### *A. Transfer of Sacks From the Slide to a Cart or a Conveyor Belt*

At this workstation (Fig. 1), mail sacks come down a large slide and are manually loaded onto the nearest conveyor belt or cart. The sacks are frequently very heavy and difficult to grasp due to a lack of an operator interface; this, in turn, results in inefficient operation. The slides and conveyor belts are clearly accessible from above, and the carts used to receive the sacks are open on top. Robotic systems with end-effectors like those described here can be installed above to automatically load sacks onto conveyor belts or carts.

### *B. Sack Sorter*

At the workstation shown in Fig. 2, mail sacks, each weighing from 10 pounds (4.5 kgf) to 70 pounds (32 kgf), travel down a narrow chute, and drop onto conveyer rollers before being transferred manually onto rolling carts. Each sack sorter has 15 to 20 carts arranged around the roller. Since the conveyer roller is accessible from both sides, the sorting process is naturally divided between both sides of the conveyer roller. It would therefore be possible to construct two robotic systems that do not interfere with each other, one on each side of the conveyor roller.

The following key specifications for the end-effector were identified after studies of the workstations and processes.

Fig. 1. USPS distribution center where thousands of sacks are unloaded off a large slide and emptied onto carts by hand.

Fig. 2. In some distribution centers, the mail sacks travel down a narrow chute and drop onto conveyor rollers, and are then manually moved directly onto rolling carts based on destination.

- The end-effector must be able to grab and hold a sack of any shape and size from any point on the sack. In other words, the end-effector should not demand a gathered and flattened edge of the sack, and it should not need a pre-defined orientation of the sack to grasp the sack. The mail sacks do not feature handles, eyelets or other operator interfaces. They assume a wide variety of shapes, sizes, and colors, and each weighs up to 70 pounds (32 kgf).
- The robot and the end-effector must grasp and manipulate these sacks continuously for long periods without dropping any. This requirement places a hard constraint on the grasp-speed and grasp-robustness of the end-effector. If, due to high acceleration of the robot maneuver, the end-effector drops a sack, an operator must enter the robot cell for recovery, which results in process downtime for cell shutdown and robot re-initialization.

The end-effector described here is capable of creating very large grasp forces and has a wide bandwidth (i.e., high speed) for grasp operation. Therefore, the robot bandwidth will be the limiting factor in overall system throughput.

## II. Background on Robotic Grasping Methods

Many robotic end-effectors have been proposed for use with robot arms as grasping hands. The simplest of these consists of simple parallel-jaw grippers. However, the resulting two-point contact is insufficient to maintain a stable grasp. More complex systems include designs which mimic the human hand. However, anthropomorphic designs, with their large number of degrees of freedom, can become too complex and cumbersome for certain applications. In fact, the actuators of the anthropomorphic designs must be placed at locations other than at the palm or wrist due to their sizes. Jacobsen *et al.* [6] describe a four-finger pneumatically powered hand. Salisbury [10] gives details on an electrically powered three finger hand with stiffness control. Jau [7] presents a four-finger electrically powered hand capable of creating rolling motion for objects. Sugano and Kato [12] describe the design of a five-finger hand for playing musical instruments with little grasping and manipulation capability. These complex anthropomorphic robotic hands, although promising for dexterous manipulations of objects, are in practice more suitable for handling objects of well-defined geometries than compliant objects. Parallel with research efforts in design and construction of various grasping hands, the research efforts on control and dynamics of grasp and manipulation (two major branches of robotics) were conducted mostly for objects with well-defined geometries. Such efforts have been reported by Casalino *et al.* [1], Fearing [2], Goldberg [3], and Mishra and Silver [8]. Okada and Rosa [9] described an end-effector with rollers for manipulation of an object using the rolling action of the rollers after the object is grasped. Recent progress by Hirai and Wada [5], [13] in development of control laws for positioning multiple points of an extensible cloth has inspired researchers to develop a device and methods to manipulate cloth and flexible objects.

Currently, there is no industrial robotic hand for grasping deformable objects with undefined shapes such as sacks. After extensive literature research, we concluded that to design an end-effector for grasping and manipulating objects other than those with well-defined shapes, one needs to depart from general-purpose robotic end-effectors and hands described above. This compromise shifted our focus to special-purpose material handling systems. In particular, paper handling systems such as printers and copiers motivated us to design a series of special-purpose end-effectors with restricted grasp and manipulation capabilities but exceptional effectiveness in grasping sacks. The end-effectors described here include rollers with rough surfaces for friction. Similar to paper handling systems, the frictional force of the rollers is the main driving force to move the objects. Refer to the research work by Gupta and Strauss in [4] and, Soong and Li in [11] where models, control, and design rules for paper handling systems have been discussed. When the end-effector comes into contact with a deformable object, the rollers drag the objects into the area between the rollers. The end-effector described here can grab and hold filled sacks from any point on the sack, regardless of sack orientation. We have

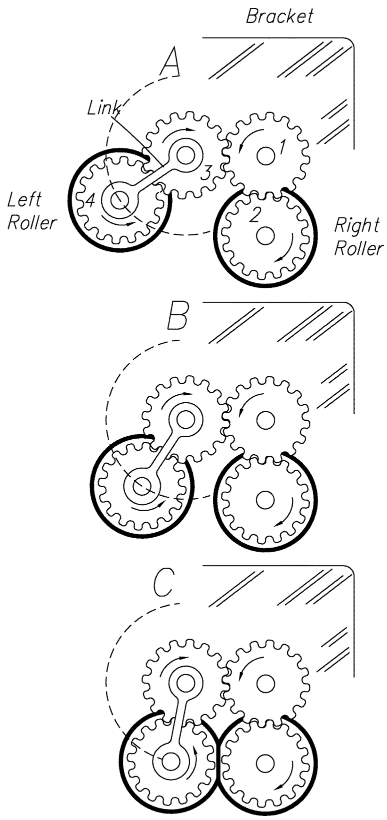


Fig. 3. Link shown above is not connected to Gear 3 and turns independently of Gear 3. The rotation of the link along the dashed line allows the rollers to come in contact with each other or separate from each other.

evaluated the end-effector experimentally and proven it exceptionally effective in grabbing sacks.

## III. Basic Principle

Fig. 3(a)–(c) depicts the basic architecture of our end-effector's grasping mechanism. As shown in Fig. 3(a), the grasping mechanism is comprised of four gears. Gear 1, in contact with Gear 2 and Gear 3, is secured to an input shaft and powered by an actuator [not illustrated in Fig. 3(a)–(c)], which enables it to turn both clockwise and counterclockwise. A bracket holds the axes of the three gears 1, 2 and 3, such that the gears are free to rotate without the axes moving relative to one another. Gear 4 is in contact with Gear 3, and therefore, turns along the opposite direction of Gear 2. A link, shown in Fig. 3(a), while holding Gear 4, turns independently of the rotation of Gear 3. In other words, the link shown in the Fig. 3(a)–(c) is able to position the axis of Gear 4 at any point on the dashed line regardless of the rotation of the gears.

As shown in Fig. 3(a), Gears 2 and 4 always turn in opposite directions. Two rollers are rigidly connected to Gear 2 and Gear 4 and therefore turn in opposite directions relative to each other. Fig.3(b) and (c) depicts two configurations as the link turns counterclockwise, bringing Gear 4 closer to Gear 2. The rotation of the link along the dashed line allows the rollers to come in contact with or separate from each other. Fig. 3(c) illustrates a configuration in which the link has turned counterclockwise, causing the rollers to push against each other. In order to push the two rollers against each other, a spring (not shown) is

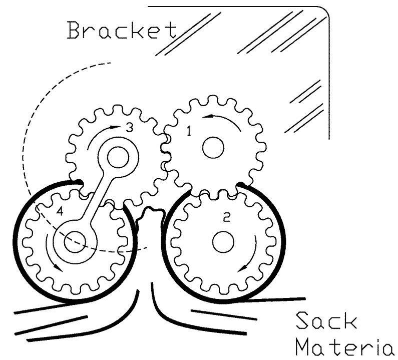


Fig. 4. When the rollers come in contact with a sack, the gears turn the rollers inwardly to grab and drag the sack into the end-effector via frictional forces.

installed between the link and the bracket to rotate the link counterclockwise, bringing the rollers close to each other. There are many means to install a spring to push the link counterclockwise, one of which is described in later sections.

The surfaces of the rollers may be knurled, grooved, stippled, or covered by frictional material such as soft rubber. When the rollers turn inward and come in contact with the sack (as seen in Fig. 4), the sack will be grabbed and dragged into the end-effector by the frictional forces between the rollers and the sack's material. As the rollers continue to turn, more material will be pulled in between the rollers. The rollers stop when sufficient amount of sack material is grabbed. This is facilitated by a sensor switch (described in later sections) in the end-effector, which issues a signal to stop rotation and lock the gears when sufficient material is pulled into the region between the rollers. The friction between the rollers and the sack material will not allow the sack to slide out of the end-effector. Depending on the sack material, an appropriate roller surface can be selected to provide sufficient friction. The caught sack will not slide out, provided that the gears are prevented from rotating, the rollers are pushed together tightly by a spring, and a sufficiently large friction exists between the sack material and the rollers. Once secured, the sack can be maneuvered by a material handling device, such as a robotic arm or a hoist. To release the sack, the rollers should be rotated outward (turning the right roller in Fig. 4 counterclockwise and the left roller clockwise). The material is thus pushed out of the end-effector and the sack is released. An alternative approach is to simply separate the rollers from each other.

To maintain a strong grip on the sack, both rollers are covered by material with a large frictional coefficient, such as rubber (e.g., Neoprene). Most importantly, the rollers must have equal linear velocities at their outer surfaces to prevent sliding motion between the rollers. If rollers slide relative to each other, the rubber coating will wear off and, in extreme cases, generate a great deal of heat, causing damages to the sack or other surrounding components. Rollers with equal diameters must have equal angular velocities to prevent sliding motion between them. To achieve this end, Gears 2 and 4 must be chosen such that $n_2 = n_4$ where $n_2$ and $n_4$ represent the number of teeth on Gears 2 and 4. If the rollers have unequal diameters, Gears 2 and 4 must be chosen such that $R_{\text{Right}} \times n_4 = n_2 \times R_{\text{Left}}$ where $R_{\text{Right}}$ and $R_{\text{Left}}$ are the radii of rollers shown in Fig. 4.

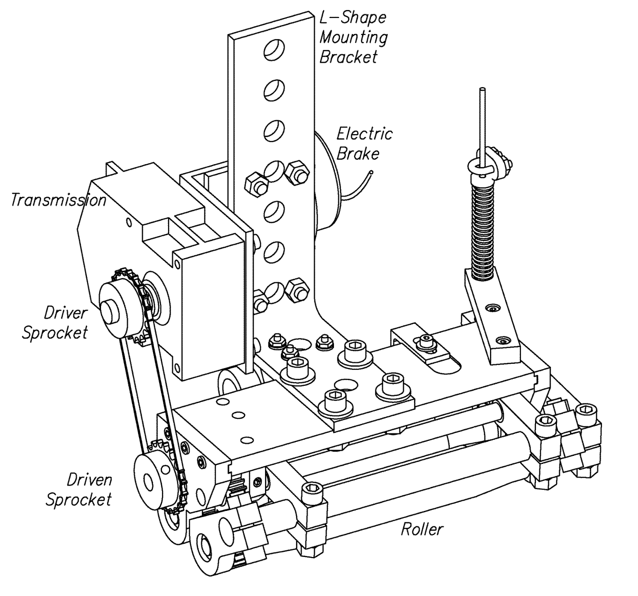


Fig. 5. Driver sprocket is secured to the transmission output shaft of the speed reducer transmission. The driven sprocket turns a shaft, which powers the grasp mechanism underneath the horizontal plate.

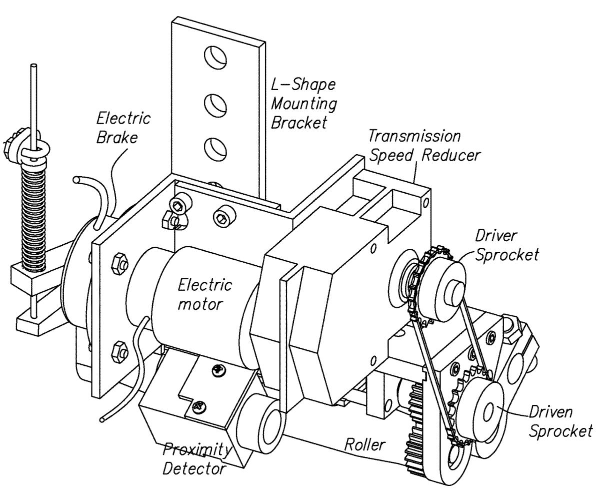


Fig. 6. Electric brake is installed on the mounting bracket to lock the motor when needed. When the brake is not powered electrically, it is engaged, preventing the motor shaft from turning.

The sack contents (boxes, letters, and magazine bundles) will never enter the inner space between the rollers. Only the sack materials (e.g., cloth) will be dragged quickly into the space between the rollers. The sack contents are free, and therefore remain in their place without being damaged. Also note that only a couple of inches (a few centimeters) of the sack material (i.e., fabric) will go into the space between the rollers. This is the novelty of this end-effector design; it grabs a sack by its fabric, using the friction force between the rollers, without any contact with the sack contents. Next, we will describe how this friction force is created via a novel hardware.

## IV. Prototype System for U.S. Postal Services

Adopting the grasping mechanism shown in Figs. 3 –6 show two different views of an end-effector designed for USPS applications. Due to its light weight and small volume, an L-shaped mounting bracket was chosen to support the major components of the end-effector. A supporting bracket assembly is installed on the horizontal section of the L-shape mounting bracket to support the entire grasping mechanism.

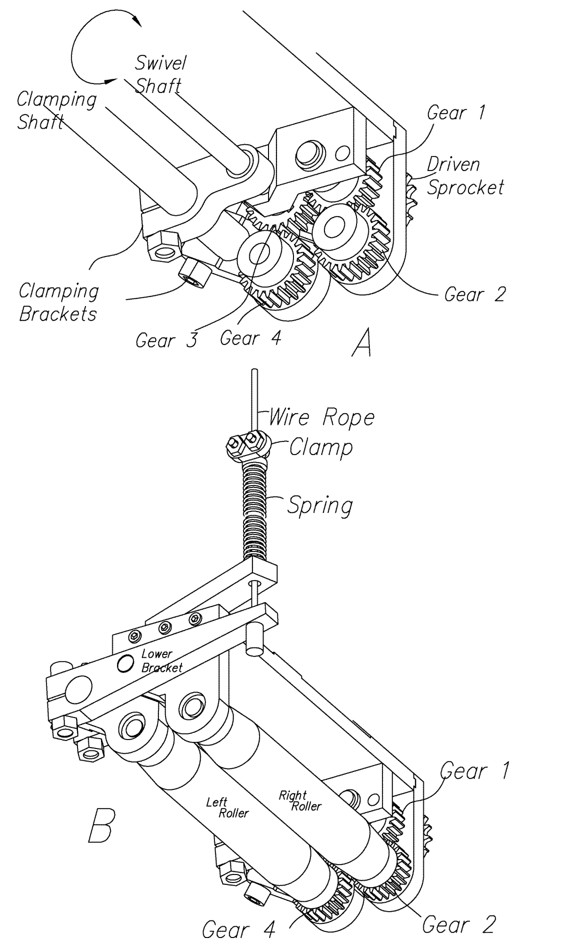


Fig. 7. (a). Beneath the end-effector with the rollers removed. (b) Spring that pushes the left roller against the right roller.

As shown in Fig. 6, the actuator turning the rollers is comprised of an electric motor coupled to a speed reducer transmission. A single-phase 0.2 HP DC motor, powered by a 12 VDC power supply, was chosen to power the end-effector. Additionally, the speed reducer transmission has a speed ratio of 36, resulting in output torque 70 lbf-in at 180 RPM. An electric brake is installed on the L-shape mounting bracket to lock the motor when needed. When the brake is not powered electrically, it is engaged to prevent the motor shaft from turning. When the brake is electrically powered, the motor shaft is free to turn. The brake in our prototype system produces 7 lbf-inch of braking torque. A driver sprocket is secured to the transmission output shaft of the speed reducer transmission. The driver-sprocket, via a chain, drives another sprocket. The driven sprocket subsequently turns a shaft underneath the horizontal plate, thus powering the entire grasping mechanism installed underneath.

Fig. 7(a) shows the underside of the end-effector without the rollers. Two clamping brackets are installed tightly on a clamping shaft, rotating together around the axis of the swivel shaft along the arrow shown. This mechanism plays the same role as the link in Fig. 4, which is to move the center of Gear 4 along the shown arrow. Gears 1 and 3 turn in opposite directions

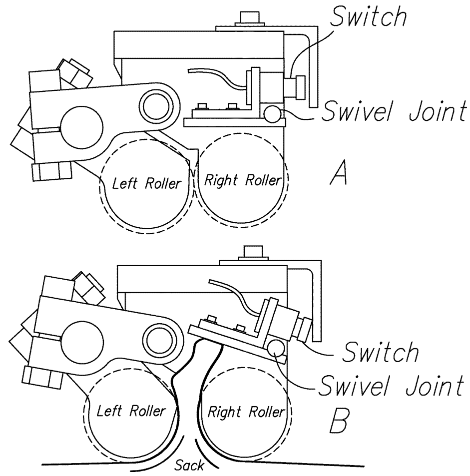


Fig. 8. Switch issues a signal when enough sack material is collected between the rollers.

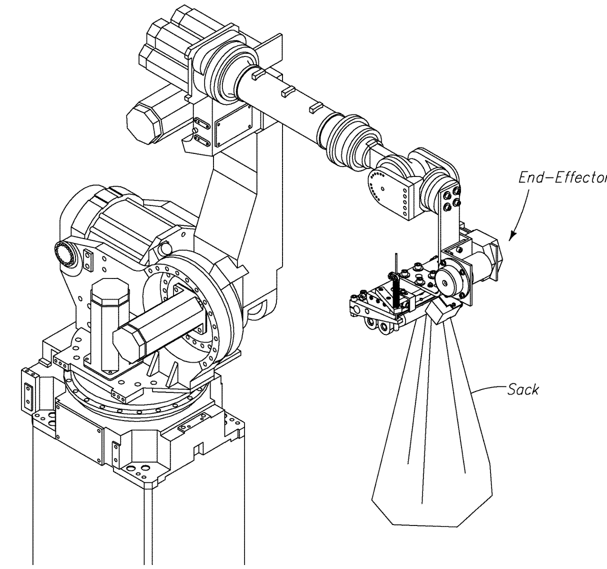


Fig. 9. Fanuc robot and the end-effector holding a sack.

relative to each other. Gears 2 and 4, in contact with Gears 1 and 3 respectively, also turn in opposite directions relative to each other. As illustrated, Gear 4 turns opposite Gear 2, but is never engaged with it. Fig. 7(b) shows the system with two rollers rigidly connected to Gears 2 and 4, turning in opposite directions relative to each other. The motion of Gear 4's axis along the arrow allows the axis of the left roller to move relative to the axis of right roller while they both spin opposite each other along their own axes. Fig. 7(b) also illustrates a spring, which pushes the left roller against the right roller. A wire rope passing through the spring is secured to a lower bracket. The clamp at the upper end of the wire rope secures it to the upper end of the spring. The spring can be preloaded by moving the clamp along the wire rope. As we lower the clamp, the increased compression force in the spring creates a tensile force in the wire rope, which rotates the lower bracket and causes the left roller to be pushed against the right.

Fig. 8 illustrates one possible configuration for the installation of a sensor switch that is responsible for signaling the system when sufficient material has been collected between the rollers. The sensor assembly consists of a momentary switch installed on an angular bracket and rigidly connected to a swivel shaft, which is free to rotate around its own axis.

Fig. 8(a) shows the end-effector with the swivel shaft in its neutral position, with the switch deactivated. Fig. 8(b) illustrates the case in which the swivel shaft turns clockwise through the force from the sack material, with the switch pressed against another stationary bracket.

The prototype end-effector described here weighs 20 pounds (9 kgf) and can be used with a variety of anthropomorphic and cartesian overhead robotic systems. The prototype end-effector has several mounting holes used to connect to a robot. Fig. 9 illustrates the experimental end-effector mounted on a robot.

## V. Control

In our prototype, a system of detectors and switches are installed on the end-effector to control its operation. The end-effector has three primary operational phases: 1) "Grab," i.e., rotate the rollers inward; 2) "Hold," i.e., lock the rollers; and 3) "Release," i.e., rotate the rollers outward. Depending on the application, the end-effector can be forced into any of the three phases. The state logic diagram of the end-effector is dependent on its use cases.

| | $S_G$ | $S_H$ | $S_R$ | End-Effector States |
|---|---|---|---|---|
| Row 1 | 0 | 0 | 0 | Hold |
| Row 2 | 0 | 0 | 1 | Release |
| Row 3 | 0 | 1 | 0 | Hold |
| Row 4 | 0 | 1 | 1 | Release |
| Row 5 | 1 | 0 | 0 | Grab |
| Row 6 | 1 | 0 | 1 | Release |
| Row 7 | 1 | 1 | 0 | Hold |
| Row 8 | 1 | 1 | 1 | Release |

Fig. 10. Operational phases of the end-effector.

A logic signal $S_G$ is used to indicate the proximity of the end-effector to a sack. In the prototype, an optical proximity detector installed on the end-effector (Fig. 6) asserts $S_G = 1$ when the end-effector comes in close proximity to a sack.

Another logic signal $(S_H)$ is issued when sufficient material has been pulled in between the rollers. In our system, an electromechanical switch installed in the end-effector asserts $S_H = 1$ when sufficient sack material is collected between the rollers. This switch is shown in Fig. 8(a) and (b).

Finally, a third logic signal $S_R$ is asserted to release the sack. This signal may be generated through various events. For instance, the sack can be released when it is placed on a desired work surface, or upon a command from an operator or a computer. Fig. 10 illustrates the operational phases of the end-effector for all possible state combinations of the logic signals $S_G$, $S_H$, and $S_R$. As seen in Fig. 10, only one combination of signals $S_G$, $S_H$ and $S_R$ forces the end-effector into the "Grab" phase. This combination is shown in Row 5 where $S_G = 1$ (the end-effector is close to the sack); $S_H = 0$ (the sack is not completely grabbed) and $S_R = 0$ (no command is issued to release the sack). There are three combinations to force the end-effector into the "Hold" phase. Row 1 indicates a case in which the sack

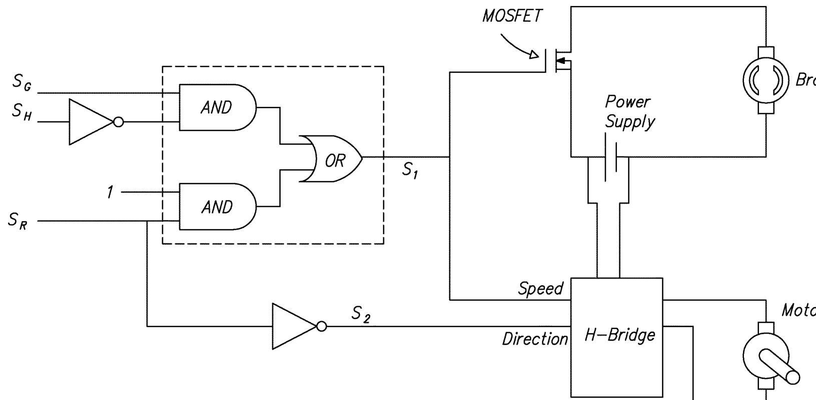


Fig. 11. Schematic representation of how $S_G$, $S_H$, and $S_R$, drive the events and operational phases of the end-effector.

is neither in nor near the end-effector, and no release command is issued. Rows 3 and 7 represent the cases in which sufficient material is gathered between the rollers, and the end-effector must thus hold the sack. The remaining combinations show that the end-effector is always forced into the "Release" phase whenever $S_R = 1$. In the prototype system, a voltage is applied to the brake coil to disengage the brake and allow the rollers to rotate. When the end-effector is in the "Hold" phase, the power is disconnected and is therefore engaging the brake. Fig. 11 illustrates schematically how the three signals $S_G$, $S_H$, and $S_R$ drive the events and operational phases shown in Fig. 10.

Signal $S_1$ is tied to two power electronic components: a MOSFET and an H-Bridge. When signal $S_1$ is high (i.e., $S_1 = 1$), the MOSFET permits current flow from the power supply to the brake, thus permitting rotation of the driver sprocket. The H-Bridge is a power electronic chipset. Its "Speed" and "Direction" input pins are connected directly to $S_1$ and $S_2$; its two output power terminals are connected directly to the motor. The H-bridge has two other inputs capable of accepting power voltages. In our prototype system, a 12-V dc power supply is used to power the motor and the brake. When $S_1$ is high, the outputs connected to the motor terminals get latched to the power supply. When $S_1 = 0$, zero voltage will be latched on the motor terminals. The "high" and "low" states of the "Direction" signal dictate the rollers' rotational direction.

## VI. Grasp-and-Hold Conditions

Some of the crucial design considerations of the end-effector are explained here in detail. In this section, we focus on the following phases of the end-effector's behavior: *prior to grasp, during grasp, after grasp* and *during hold*. The first three phases named complete the "Grab" operation, which was discussed in the previous section.

### A. Prior to Grasp

Prior to any grab and lift process, the sack is typically at rest on a floor or other surface such as a conveyor belt. Fig. 12 shows the right roller of the end-effector upon its initial engagement with the sack material. The normal vertical force between the roller and the sack material is $N_G$, a function of the normal vertical force being imposed on the end-effector and the weight of

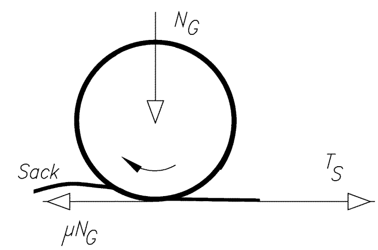


Fig. 12. Roller in its initial engagement with the sack.

the end-effector. The sacks are usually filled with heavy objects which results in a tensile force, $T_S$, present in the sack material. If this tensile force is large (i.e., the sack is over-stuffed), it would be difficult for the rollers to pull the material between them. The frictional force onto the sack from each roller $(\mu N_G)$ should be larger than the tension force $(T_S)$ of the material, so the sack material can be pulled into the area between the rollers

$$\mu N_G \geq T_S. \tag{1}$$

The tensile force in the sack $T_S$ will never be more than the weight of the contents in the sack. In other words, if the sack is filled with 40 kg of postal boxes, the maximum tensile force in the sack material will always be less than 40 kg when the sack is at rest. In an experiment, we chose normal force to be about 60 kg (larger than the sack's weight). The rollers of the end-effector may not properly engage with the sack material if the end-effector is not pushed downward with sufficient force, and if the coefficient of friction between the sack and the roller is small. To initiate the grasp successfully, therefore, both $\mu$ and $N_G$ should be sufficiently large to satisfy inequality (1). The torque needed to be imposed on the roller during this phase can be calculated as

$$T_{\text{Roller}} = \mu N_G R \tag{2}$$

where $R$ is the roller's radius. Considering inequality (1), the torque needed to be imposed on this roller during this phase is

$$T_{\text{Roller}} \geq T_S R. \tag{3}$$

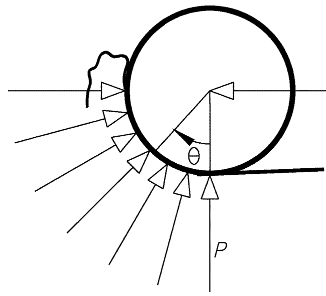


Fig. 13. Pressure profile on the end-effector roller.

By inspection of Fig. 4, the total grasp torque needed to be imposed on Gear 1 by the electric motor is

$$T_G \geq T_S \left[ R_{\text{Right}} \frac{n_1}{n_2} + R_{\text{Left}} \frac{n_1}{n_4} \right] \tag{4}$$

where $R_{\text{Right}}$ and $R_{\text{Left}}$ are the radii of the rollers and $T_G$ is the total grasp torque that is imposed on Gear 1 by the electric motor and the transmission speed reducer. $n_x$ is the number of teeth on gear X. When inequality (4) is satisfied during this phase, the grabbing process starts and sufficient sack material is drawn between the rollers. Overstuffed sacks result in a large tensile force, which makes the start of the "Grasp" process more difficult.

## B. During Grasp

As shown in Fig. 13, as sack material is collected, the pressure built up in between the rollers pushes them apart as more sack material is squeezed in. Suppose the pressure between the sack material and the roller per unit length of the roller's perimeter (circumference) is $P$, then, (5) represents the force balance for the right roller along the horizontal direction.

$$R \int_0^{\frac{\pi}{2}} (P \sin(\theta) + P\mu \cos(\theta))\, d\theta = N_H \tag{5}$$

where $N_H$ is the horizontal force on the roller attributed to the force of the spring. Pressure is defined here as the force per unit area imposed on the rollers. It is rather difficult to determine the exact pressure profile on the rollers, but since the sack material is compliant, it will move between the rollers to create a nearly uniform pressure. Substituting a constant value for $P$ into (5) results in (6) for force $N_H$

$$\text{RP}_o \int_0^{\frac{\pi}{2}} (\sin(\theta) + \mu\cos(\theta))\, d\theta = N_H \tag{6}$$

$$\text{or}: \quad \text{RP}_o(1 + \mu) = N_H \tag{7}$$

where $P_o$ is the constant pressure on the rollers. The torque turning the rollers, $T_{\text{Roller}}$, should be sufficiently large to overcome the frictional forces from the pressure on the rollers

$$T_{\text{Roller}} \geq \int_0^{\frac{\pi}{2}} \text{PR}^2 \mu\, d\theta. \tag{8}$$

Substituting the constant $P_o$ for $P$ in inequality (8) results in inequality (9) for the torque on the roller during this phase

$$T_{\text{Roller}} \geq P_o R^2 \mu \pi \frac{1}{2}. \tag{9}$$

Substituting for $P_o$ from (7) into inequality (9) results in a relationship between the force, $N_H$, and the required torque on the roller $T_{\text{Roller}}$

$$T_{\text{Roller}} \geq \frac{\mu \pi}{2(1+\mu)} N_H R. \tag{10}$$

Inequality (10) shows that the grasp torque on a roller is proportional to the normal force generated by the spring. The larger the force is between the rollers from the spring, the more torque that is needed from the motor and the transmission. By inspection of Fig. 4, (11) shows the total torque that should be imposed on Gear 1 by the electric motor and the transmission during this phase

$$T_G \geq \frac{\mu \pi}{2(1+\mu)} N_H \left[ R_{\text{Right}} \frac{n_1}{n_2} + R_{\text{Left}} \frac{n_1}{n_4} \right]. \tag{11}$$

If the electric motor and the transmission cannot provide sufficient torque, the rollers will stall.

## C. After Grasp

During high-speed operations, the end-effector might be moved upward by a robot or material handling device before completion of the "Grab" phase, when the sack is not being held firmly. To prevent the sack from getting dropped in this situation, the electric motor and speed reducer transmissions must generate sufficient torque on the rollers to assure that the rollers turn and draw enough sack material in between to force the end-effector into the "Hold" phase. When the sack is held between the rollers and the end-effector is lifted, the total upward friction forces imposed by the rollers on the sack must be greater than the sum of the weight and the inertia force from the maximum upward acceleration of the end-effector (Fig. 14)

$$2\mu N_H \geq W_{\max} \left( 1 + \frac{\alpha}{g} \right) \tag{12}$$

where $g$is the gravitational acceleration, $W_{\max}$ is the weight of the heaviest sack to be lifted, $N_H$ is the normal force imposed by the rollers onto the sack material, $\mu$ is the coefficient of friction between the rollers and sack, and $\alpha$ is the magnitude of the maximum total acceleration of the end-effector induced by the robot. During our observations, we noticed that the acceleration along the horizontal plane for most robot maneuvers in distribution areas were less than 10% of the gravity acceleration. If inequality (12) is not satisfied, the sack will slide out of the end-effector. Thus, the end-effector must be designed with its $N_H$ and $\mu$ sufficiently large to ensure that the heaviest sack will not slide out of the rollers. Inspection of Fig. 4 shows that the required grab torque imposed by the electric motor to keep Gear 1 stationary is

$$T_G = \mu N_H \left[ R_{\text{Right}} \frac{n_1}{n_2} + R_{\text{Left}} \frac{n_1}{n_4} \right] \tag{13}$$

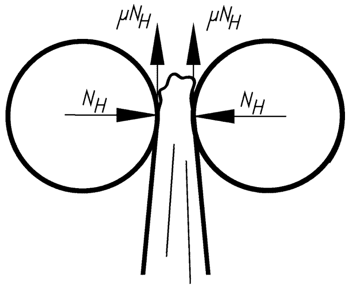


Fig. 14. Friction forces prevent the sack from sliding out.

where $R_{\text{Left}}$ and $R_{\text{Right}}$ are the radii of the rollers and $T_G$ is the grab torque imposed by the motor and the transmission on Gear 1. $n_x$ is the number of teeth on gear X. Comparing inequality (12) with (13) results in inequality (14), which represents the required grab torque on Gear 1 for this phase

$$T_G \geq W_{\max}\left(1+\frac{\alpha}{g}\right)\left[R_{\text{Right}}\frac{n_1}{n_2}+R_{\text{Left}}\frac{n_1}{n_4}\right]\frac{1}{2}. \quad (14)$$

If the rollers have equal radii, (i.e., $R_{\text{Right}} = R_{\text{Left}}$), then the number of teeth on both gears 2 and 4 should be equal to prevent slipping of the rollers relative to each other (i.e., $n_2 = n_4$). The holding torque, when the rollers have equal radii, can be calculated from

$$T_G \geq W_{\max}\left(1+\frac{\alpha}{g}\right)R_{\text{Right}}\frac{n_1}{n_2}. \quad (15)$$

In our first design, both Gears 1 and 2 have equal number of teeth and both rollers have equal radii. Three inequalities (4), (11), and (14) offer three grab torque values for the electric motor. A motor and a transmission must be selected such that the steady state output torque is larger than the largest torque value generated by inequalities (4), (11) and (14). The largest value for $T_S$, the tension force in the sack material, occurs when the sack is lifted. As $T_S$ gets larger, inequality (4) approaches inequality (14). In other words, inequality (14) yields a larger grab torque value than inequality (4). Since inequality (11) typically results in a smaller grab torque value than inequality (14), it is preferable to choose an electric motor and a transmission with a torque capability greater than what inequality (14) prescribes.

### D. Hold Phase

When the sack is held between the rollers, and the end-effector is lifted, the total upward friction forces imposed on the sack by the rollers must be larger than the total of the maximum weight and the inertia force from the maximum upward acceleration of the end-effector. This means that the required torque to be imposed by the electric brake during the "Hold" phase should be equal to the torque derived by (14)

$$T_H \geq W_{\max}\left(1+\frac{\alpha}{g}\right)\left[R_{\text{Right}}\frac{n_1}{n_2}+R_{\text{Left}}\frac{n_1}{n_4}\right]\frac{1}{2}. \quad (16)$$

If the brake torque is not large enough to satisfy inequality (16), the sack will slide out of the end-effector. Thus the end-effector must be designed with a brake torque large enough to guarantee that the heaviest sack lifted does not slide out of the rollers. If the rollers have equal radii (i.e., $R_{\text{Left}} = R_{\text{Right}}$), then, the number of teeth on both Gears 2 and 4 should be equal to prevent slipping motion of the rollers relative to each other (i.e., $n_2 = n_4$). When the rollers have equal radii, the brake torque $T_B$ can be calculated from

$$T_B \geq \frac{1}{N}W_{\max}\left(1+\frac{\alpha}{g}\right)R_{\text{Right}}\frac{n_1}{n_2} \quad (17)$$

where the ratio of the transmission input shaft's angular speed to Gear 1's angular speed is $N$. The holding torque of a brake is a function of the stiffness of the spring installed in the brake. The stiffer the spring, the more holding torque that is generated. Although more holding torque during the "Hold" phase assures that heavier sacks can be lifted, a brake with a stiff spring and consequently large holding torque requires a large amount of electric current to disengage. Also note that large speed reduction ratios make the speed reducer transmissions not back-drivable, thus helping the end-effector during the "Hold" phase. Since the rollers cannot spin outward by the force of the sack's weight, the sack material will not be released. In general, the use of nonback drivable speed reducers (such as worm gears) eliminates the need for brakes in the end-effector device.

## VII. Remarks on Performance and Tradeoffs

As a general guideline, we recommend the designers use inequalities (14) and (16) to calculate the motor torque and the brake torque while inequality (12) is satisfied to ensure that the sack remains between the rollers. The design issue associated with friction between the rollers and the sack material is described below. A large coefficient of friction between the rollers and the sack material can be achieved in a variety of ways. Knurled rollers are effective in grabbing sacks but can damage them. Another method of creating friction is to wrap the rollers with a rubber or rubber-like material that has a large coefficient of friction. However, rubber with a large coefficient of friction is usually soft and wears off too soon. Inspection of inequality (12) shows that large values for $\mu$ and $N_H$ allow the end-effector to lift heavy sacks. However, one cannot design an end-effector with a large normal force $(N_H)$ and a large coefficient of friction $(\mu)$ because there is a trade-off. As seen in inequality (13), large values for $N_H$ and $\mu$ require high torque actuators. If large $N_H$ and $\mu$ are chosen to guarantee inequality (12), then a large actuator should also be chosen to overcome frictional forces between the rollers. In other words, one cannot arbitrarily choose a stiff spring to generate a large $N_H$; practitioners must arrive at a value for the spring stiffness and rubber coefficient of friction, so that inequality (12) can be satisfied with a reasonable margin. Overdesigned systems (i.e., those with a very a large $\mu$ and $N_H$) will require unnecessarily large actuators and power supplies. On the other hand, if the spring is not stiff enough to generate a sufficiently large $N_H$ to satisfy inequality (12), the rollers will not be sufficiently pushed together, and the sack will slide down. Once an optimal material that possesses a good coefficient of friction and has a long life is chosen for the rubber on the rollers, one must choose a spring with proper stiffness for the end-effector to yield an appropriate normal force to satisfy inequality (12). In general, a large coefficient of friction for rubber requires softer springs, and a small coefficient of friction requires stiffer springs.

## VIII. Design Example

Suppose the heaviest sack to be lifted by our experimental end-effector is 70 pounds (32 kgf) and the maximum maneuvering acceleration for the robot is 0.3 g. The rollers' radii are chosen as 0.7″ (18 mm). Below we derive a value for the grab torque, brake torque and the force in the spring.

Substituting for $\alpha$, $W_{\max}$ and $R_{\mathrm{Right}}$ in inequality (15) results in at least 63.7 lbf-in (7.2 N·m) of grab torque on gear 1 during the "grab" phase. A single-phase dc motor and transmission system, capable of supplying 70 lbf-in (7.9 N·m), was chosen to power the end-effector.

The chosen motor and transmission system has a transmission ratio of 36. Substituting for $\alpha$, $W_{\max}$ and $R_{\mathrm{Right}}$ in inequality (17) results in at least 1.76 lbf-in (0.2 N·m) of brake torque during the "hold" phase. In our experimental system, we used a normally engaged brake capable of supplying 7 lbf-in (0.8 N·m) holding torque and requiring 0.477 A at 12 VDC to disengage.

Neoprene with $\mu = 1$ was chosen for the first experimental system. The spring's pre-load is adjusted to yield 50 lbf (222 N) between the rollers to satisfy inequality (12). If the heaviest sack to be lifted by the end-effector is 70 pounds (32 kg) and the maximum maneuvering acceleration is 0.3 g, then inequality (12) will be satisfied.

## IX. Application Notes

This article depicts a robotic end-effector for grasping deformable objects with undefined shapes such as sacks and bags. The end-effector described here.

- It grabs a sack from any point.
- It does not require the edge of the sack to be gathered and flattened prior to grasp.
- It does not require the sack to be placed on its bottom prior to grasp (i.e., the sack can be laid on the floor or on a conveyor belt from any side.)
- It does not require operator intervention to grasp.
- It does not use the weight of the sack to lock and secure the sack in the end-effector.
- It does not damage the sack contents.

Typically, the end-effector described here does not require any vision system to operate. In the absence of a vision system, the sacks need to be directed, using conveyors, to a particular location accessible by the robot. Once the sack reaches this predetermined location, the robot will move toward the sack. An optical proximity detector, located on the end-effector, starts the end-effector's operation (as described above) when it detects a sack in close proximity of the end-effector. Based on our experience, the use of a particular end-effector in industry is the result of many variables, most of which are application dependent. Although we have not conducted a great deal of experiments to grasp other objects, we can confidently claim that the end-effector described in this paper is effective in grasping sacks. Through experiments we recorded that the end-effector failed three times during one hundred grasp and lift trials. All failures were caused by faulty components (i.e., chain, connectors and sensors) with no direct connection with the basic concept described here. Fig. 15 shows the experimental end-effector holding a U.S. postal sack. Fig. 16 shows the end-effector during one of our experiments in grasping a parcel bin (i.e., a plastic box without a top, used for mail handling). The thin walls of these boxes perform similarly to sack materials. Of course, if a box has a top surface, suction cups are always superior over any other grasping device.

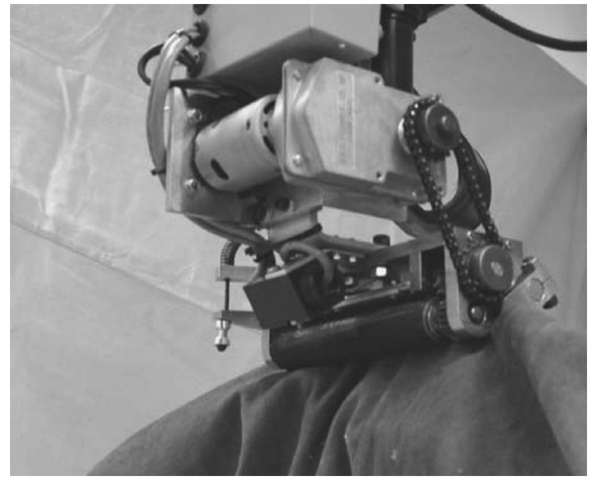

Fig. 15. Robot and the end-effector holding a sack.


Fig. 16. Experimental end-effector holding a parcel bin.

## X. Conclusion

We developed an end-effector which can grab any point of a compliant sack without any operator intervention and regardless of where and how the sack is placed. An entirely different and effective concept for grasping sacks was described in this article. When the end-effector comes in contact with a sack, the sack material will be grabbed and pulled quickly into the end-effector without any intervention from the operator.

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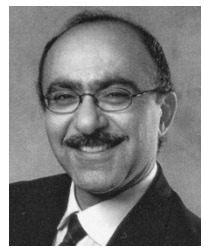

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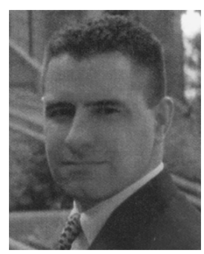

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