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A Robotic End-Effector for Grasping Postal Sacks

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Abstract

This article describes a new class of end-effectors that can be used with robotic and material handling devices for grabbing and holding deformable objects with undefined shapes such as sacks and bags. These end-effectors can grab and hold filled sacks from any point on the sack and regardless of the sack orientation and position. The first prototype end-effector, designed for U.S. Postal Service, has two rollers. The rollers are pushed toward each other by the force of a spring. When the rollers are powered to spin, the inward spinning of the rollers causes the sack material to be dragged in between the rollers due to the friction between the surfaces of the rollers and the sack material. The spring pushes the rollers toward each other with sufficient force to hold the sack material in place between the rollers. The end-effector described here has been evaluated and proven to be effective in grabbing and holding postal sacks.

1) BACKGROUND

Delivery and postal services around the world currently use sacks to hold letters, magazines and small boxes. These sacks are handled manually by mail handlers in postal service distribution centers. Most sacks used by the U.S. Postal Service (USPS) do not have eyelets, handles or any form of operator interface for lifting and carrying. The shape, size and weight of a sack depends on the items in the sack and how it rests on a floor or on a conveyor belt. The sacks in postal distribution centers that are filled fully with magazine bundles can weigh up to 70 pounds. The heavy weight of these sacks, the lack of handles, eyelets or other operator interface on the sacks, and the unpredictable shape and size of the sacks create awkward and uncomfortable handling situations for mail handlers at all USPS distribution centers. Figure 1 shows a USPS distribution center where the sacks come down a large slide and are manually loaded onto either the nearest conveyor belts or onto carts. The sacks are often very heavy and without an operator interface of any kind, they are difficult to grasp. This makes the sack sorting process very slow and inefficient. This awkward sack handling, in particular during repeated maneuvers, has increased the risk and occurrence of wrist, finger and back injuries among mail handlers.

To minimize the risk of injuries to workers, research work was done, to automate the sack handling stations in distribution centers using robots equipped with robotic end-effectors and vision systems. The design of the robotic end-effectors used to grab sacks and bags was one of the primary foci of this research work and is described in this article. There are two specifications associated with the end-effector:

- The end-effector must grab and hold a sack regardless of the shape and size of the sack from any point on the sack (i.e., the end-effector should not need a gathered and flattened edge of the sack or it should not need to have the sack to be in a particular orientation prior to grasp). The mail sacks have no handles, eyelets or other operator interface, and they come in a variety of shapes, sizes and colors, but they weigh less than 70 pounds.
- The robot and the end-effector must grasp and manipulate six (6) sacks per minute for four hours without any drop. This places a hard constraint on the grasp robustness of the end-effector. Any time that the end-effector drops a sack, an operator needs to enter the robot cell for recovery, which leads to process downtime due to cell shutdown and robot initialization.

Figure 1: An example of a USPS Distribution Center in Northern California where thousands of sacks are unloaded off a large slide and either emptied directly onto conveyor belts, or loaded onto carts by hand.

Our extensive literature search on grasp and manipulation [2-5] did not yield any practical approach that allows us to grasp and hold a sack using an existing multi-finger robotic hand. This is because most advanced research efforts described by on grasping and planning are appropriate for grasping and manipulating objects with well-defined shapes and geometries that originate from industrial components. Moreover, the end-effectors themselves are designed and built for grasping industrial components. We have concluded that the lack of biologically inspired hardware has hampered progress in robotic grasping of unknown objects in unstructured environments. This forced us to compromise and design robotic end-effectors that grasp sacks and bags only. The robotic end-effector described here grabs and holds a sack regardless of the shape and size of the sack from any point on the sack (i.e., it is not necessary to gather and flatten the edge of the sack or orient the sack prior to grasp.) This end-effector has been tested extensively and proven to be effective in grabbing and holding sacks. This article describes the hardware architecture, the control method and the design issues associated with the end-effector. Detailed description is given in reference [1].

2) BASIC PRINCIPLE

Figure 2A and Figure 2B schematically illustrate the basic principle behind the end-effector described here. The end-effector comprises of two rollers, which are able to rotate along their own axes respectively. Both rollers are powered and can rotate in both clockwise and counterclockwise directions. There are many ways to transmit torque to rollers, however, Figure 2A and Figure 2B are drawn without any source of power for the sake of clear illustration and understanding of the basic principle of this end-effector. Other figures in this paper show the source of power and the method of transmitting power to the rollers. Two holding brackets pivot relative to each other and hold the rollers at their other ends. A spring is connected to holding brackets and forces the holding brackets toward each other. The surfaces of the rollers are gripping surfaces, which are covered by frictional material such as soft rubber, or being knurled, grooved, or stippled. As shown in Figure 2A, when the rollers are turned inwardly, and the rollers come in contact with a sack, the sack material will be grabbed and dragged into the end-effector due to the interaction (e.g., friction forces) between the rollers and the sack material. As rollers continue to turn, more sack material will be dragged in between the rollers as shown in Figure 2B. When sufficient sack material has been grabbed, rotation of the rollers is stopped. This is facilitated by a sensor switch (described in later sections) installed in the end-effector which issues a signal to stop rotation and lock the rollers when sufficient sack material has been dragged into the inter-roller 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 between the rollers and the sack material to hold the sack. As long as the rollers are locked and prevented from rotating and the spring pushes the rollers tightly together, and as long as the coefficient of friction between the sack material and the rollers is sufficiently large, the sack will not slide out of the end-effector. While secured in this manner, the sack can be maneuvered by manipulating the end-effector with a material handling device such as a robot arm or a hoist. When the rollers are rotated outwardly, the sack material, which had been grabbed by the rollers will pass out of the end-effector and the sack will be released. Another method of releasing the sack is to separate the rollers from each other.

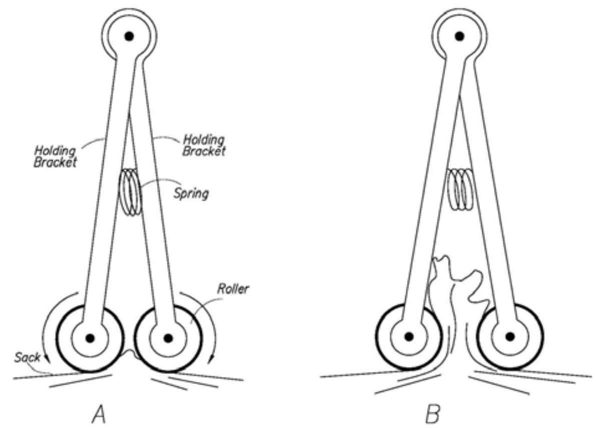

Figure 2: The basic underlying principle of operation of the end-effector.

3) A PRACTICAL IMPLEMENTATION

Figure 3 shows a practical implementation of the end-effector described by Figure 2. The first roller is able to rotate along its own axis while being held between two holding brackets. Similarly, the second roller is able to rotate along its own axis while being held between two other holding brackets. Standard ball bearings, have been installed in the holding brackets at the roller receiving points to allow smooth rotation of rollers. A shaft is held tightly between two horizontal brackets and provide a mounting point at which the end-effector may be attached to a robot or a material handling system. Attachment points (e.g., threaded holes) have been provided on the shaft brackets to facilitate attaching end-effector to a material handling device. The overall function of two horizontal brackets is to hold the shaft and connect the end-effector to robot or to a material handling system. The holding brackets that hold the first roller are free to rotate on the shaft. The holding brackets that hold the second roller are tightly fixed to the shaft and therefore do not turn or pivot on the shaft. This is done by means of tightening screws. This arrangement allows the first roller to move relative to the second roller. Two springs pull the holding brackets of the first roller toward the holding brackets of the second roller. Two actuators via two flexible shafts power the rollers. Each actuator consists of an electric motor coupled to a speed reducer transmission. By properly powering the actuators, the rollers are able to turn in both clockwise and counterclockwise directions. The electric motors employed in this design are single phase 0.2HP motors powered by a 24 VDC power supply. Both speed reducer transmissions have a speed ratio of 36. The output torque of the transmission speed reducer at 180 RPM is 65 lbf-inch. Two brakes used in this design are powered by a 24 VDC power supply. The brakes are normally engaged when not powered electrically, and prevent the motor shafts from turning.

When the brakes are electrically powered, they are disengaged, and the motor shafts are free to turn. The brakes used in the first experimental system produce 3 lbf-inch braking torque.

Two motors are wired such that their respective rollers turn in opposite directions when the motors are operated. When both motors are operated such that the rollers turn inwardly, the sack material contacted by the rollers, is grabbed and drawn in between the rollers. When sufficient sack material is grabbed in between the rollers, the end-effector controller (described in later sections) stops the motors, causing the brakes to engage and prevent the rollers from rotating. With the motors prevented from turning and the rollers locked (zero angular speed is generated for the rollers), the sack material will be secured between the rollers and the sack can be maneuvered by manipulating the shaft brackets. As long as the rollers are pushed toward each other sufficiently by the springs, and the coefficient of friction between the sack materials and the rollers is sufficiently large, the sack will not slide out of the end-effector. When the rollers rotate outwardly, the sack material grabbed by the rollers will come out of end-effector, and the sack will be released. Of course, an alternative means to release the sack material from the end-effector is to separate the rollers from one another

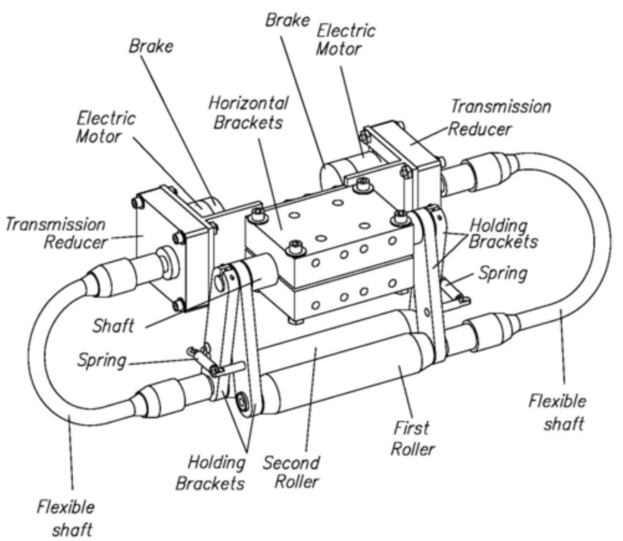

Figure 3: A perspective view of the experimental prototype end-effector that has the basic functional characteristics depicted by Figure 2.

4) LOW LEVEL CONTROL

The control of the end-effector includes a system of sensors or switches installed on the end-effector to control its operation. The end-effector has three operational phases:

1) Grabbing: rotating the rollers inwardly;
2) Holding: preventing the rollers from rotating in any direction; and
3) Releasing: rotating the rollers outwardly.

Depending on the application and sequence of operation, the end-effector can be forced into one of the three phases. The logic of how the end-effector can be forced into a particular phase depends on how and where the end-effector is being used. The following describes the low level controller for the USPS end-effector.

A logic signal, S_G, is used to indicate the proximity of the end-effector to a sack or an object to be grasped. A proximity sensor is installed on the end-effector and generates a signal (S_G becomes 1) when the end-effector is in close proximity of a sack or other object to be grasped. Rather than using a proximity sensor to recognize the nearness of the sack to the end-effector, one could use a electro-mechanical switch installed on the bottom of the end-effector to issue a logic signal when the switch contacts the sack. Another logic signal, S_H, is issued when sufficient sack material has been dragged in between the rollers. An electro-mechanical switch was installed in end-effector to send a signal (S_H becomes 1) when sufficient sack material has been dragged in between the rollers. Finally a third logic signal, S_R, is needed to flag that the sack must be released. Note that in many applications one may not want to release the sack until the sack is completely put on the floor or on the conveyor belt while in other situations one may desire to release the sack upon a command from a computer or from an operator.

Figure 4 illustrates the operational phases of the end-effector for all possible combinations of the states of three signals S_G, S_H and S_R. Note that there is only one combination of signals S_G, S_H and S_R which forces the end-effector into the "Grab" phase. This combination is shown in row 5 of the table where S_G is "1" (the end-effector is close to the sack); S_H is "0" (the sack is not completely grabbed) and S_R is "0" (no command is issued to release the sack). Also note that there are three possibilities (rows 1, 3 and 7) that force the end-effector into the "Hold" phase. Row 1 indicates the operation of the end-effector when it is being maneuvered without any sack in the end-effector while the end-effector is not close to any sack and no signal is issued for release of the sack. Row 3 and row 7 indicate that sufficient sack material has been grabbed, therefore the end-effector should hold the sack regardless of the state of S_G (The proximity sensor can see other sacks and objects nearby while it is holding a sack). The remaining combinations (rows 2, 4, 6, and 8) indicate the situation where the end-effector is forced into the "Release" phase. The end-effector is forced into the "Release" phase when S_R is "1" regardless of the states of S_G and S_H. It is straightforward to generate the "Grab" and "Release" phases of the end-effector: "Grab" indicates inward rotation of the rollers (to draw sack material into the end-effector) while "Release" indicates outward rotation of rollers (to eject material from the end-effector). However there are many methods of forcing the end-effector into "Hold" phase (preventing the rollers from turning in either directions.) One method is to install brakes on the motor shafts, on the transmission shafts, on the rollers themselves or on any rotating component connected to the rollers. The brakes are electrically powered, and engage the motor rotating shaft and stop the shaft when they are not electrically powered. These brakes employ a spring to push its brake pad onto the rotating shaft when the brake coil is not electrically powered. When voltage is imposed on the brake coil, then the brake will disengage allowing the shaft to rotate. When the end-effector is in the "Hold" phase, the power will be disconnected both from the actuators and the brakes. This causes the brakes to engage and no power is given to the actuators. It is also recommended that the terminals of the electric motors to be shorted when the end-effector is forced into "Hold" phase. This option adds more braking torque (regenerative brake) to the rollers. An alternative to regenerative brake is to develop a closed loop position controller for the motors that drive the rollers. When the system is forced into "Hold" phase, a position controller controls the angular position of the rollers at their current positions and prevents the rollers from rotating in either directions. This approach, although more effective than shortening the terminals of the motors, might be relatively costly since it requires installation of the position sensors and feedback circuitry.

	S_G	S_H	S_R	End-Effector Phases
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

Figure 4: The operational phases of the end-effector as a function of the states of three control signals.

Figure 5A and Figure 5B illustrate an example of the controller to accomplish the operational phases described above and in the truth table of Figure 4. Depending on the application, the three logic signals S_G, S_H, and S_R can be generated by a variety of devices individually or in combination. In the experimental system here, the S_G signal is generated by an electronic proximity sensor and the S_H signal and S_R signal are generated by electro-mechanical switches. Three relays A, B, and C are used to achieve the operational phases described above and shown in the truth table of Figure 4. Figure 5A is a schematic of how three signal sources (sensor/switches S_G, S_H and S_R) were wired to power three relays A, B, and C for accomplishing the events and operational phases shown the table of Figure 4. Figure 5B is a schematic of how relays A, B and C (all with two contacts) are interconnected to form a control system for operation of the end-effector. In the present example, it is assumed that all of the electrical components can utilize the same power source (24 Volt DC in this case). The normally open contacts of relays A and B (A1, A2, B1, and B2 shown in Figure 5B) disconnect each motor's terminals from the voltage source. Relay C has two contacts: a normally closed contact C1 shorts the electric motors terminals, and a normally open contact C2 disconnects power from the brakes. When relay A and relay C are energized and relay B is de-energized, the terminals of the electric motors are connected to the power source via contacts A1 and A2, the brakes are connected to the power source via contact C2 (disengaging the friction pads) and the electric motors turn the rollers inwardly, and the "Grab" phase is accomplished. When relays B and C are energized and relay A is de-energized, the terminals of the electric motors are connected to the power source via contacts B1 and B2, and the brakes are connected to the power source via contact C2 (engaging the friction pads) and the electric motors turn the rollers outwardly, and the "Release" phase is accomplished. When all relays A, B and C are de-energized, the terminals of both motors are shorted by contact C1, creating regenerative braking, and the brakes being disconnected from power source by contact C2 causes the friction pads to engage, and the rollers are held stationary, and the "Hold" phase is accomplished.

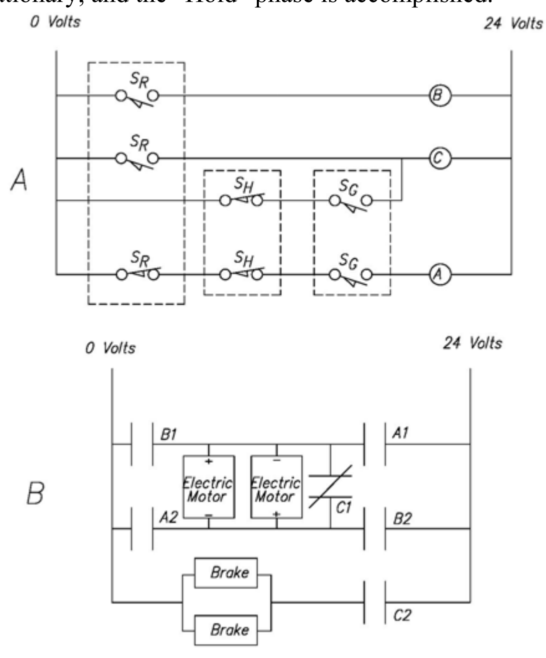

Figure 5: Three relays are wired with switches and sensors to create the behavior described in Figure 4.

Signal source S_G comprises a double pole proximity detector switch wired to have two normally-open contacts. Signal source S_H is a double pole momentary switch and is wired to have two normally-closed contacts. Signal source S_R is a triple pole momentary switch and wired to have two normally-open contacts and one normally-closed contact. By inspection of Figure 5A and Figure 5B, one can see that the end-effector can be forced into any of the operational phases shown in the table of Figure 4 depending on the combined signal conditions of detectors and switches S_G, S_H and S_R. Figure 6 illustrates our choice for installing a proximity sensor to generate a S_G signal. The proximity sensor is installed on the end-effector to issue a S_G signal when the object is detected within a predetermined distance. The proximity sensor is configured to have an appropriate angle, so that the detector beam aims at the sack. The proximity sensor issues a S_G signal (S_G becomes 1) when the end-effector is close to the sack.

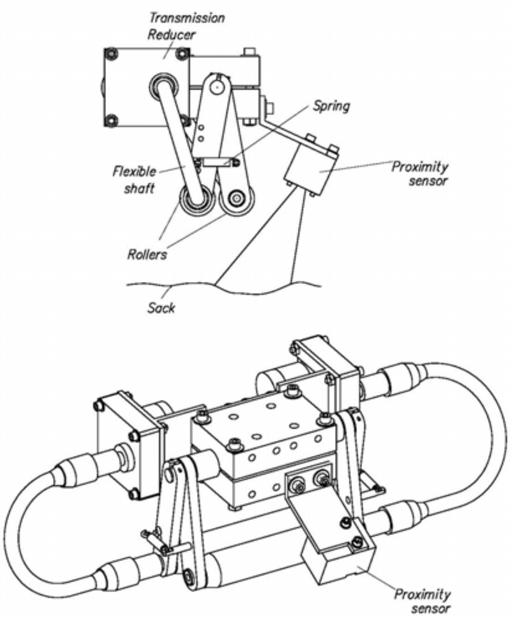

Figure 6: A proximity sensor is installed to indicate the nearness of the sack to the end-effector.

Figure 7A and Figure 7B show one possible configuration for installation of a switch to issue the S_H signal. The sensor assembly comprises a momentary switch installed on an angular bracket, which is rigidly connected to a swivel shaft. The swivel shaft is free to rotate around its own axis, but it is installed on the right holding bracket . Figure 7A shows the end-effector where the swivel shaft is in its neutral position and the switch is not activated. Figure 7B shows end-effector when swivel shaft has turned in a clockwise direction due to the force from sack material, and the switch is pressed against another stationary bracket.

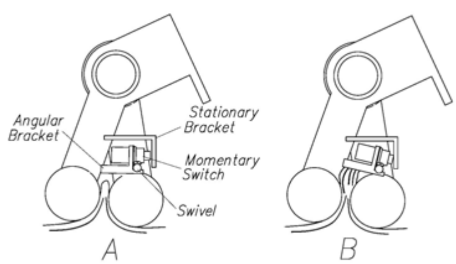

Figure 7: A switch issues a signal when enough sack material has been collected in between the rollers.

5) STABLE GRASP CONDITIONS

A description for some of the important design issues associated with the end-effector is given below. One important design issue is the calculation of the required torque during the "Hold" phase (i.e. when the sack material is dragged in between the rollers and the rollers have stopped turning). Figure 8 shows that when the sack material is held between the rollers and lifted, the total upward friction forces imposed on the sack by the rollers is calculated by equation (1):

$$\text{Upward Friction Forces} = 2\ \mu\ N_H \qquad (1)$$

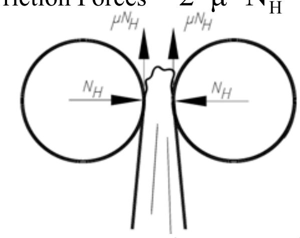

Figure 8: The contact forces and friction forces between the rollers and sack when the sack is held in between the rollers.

Where N_H is the normal force imposed by the rollers onto the sack during the "Hold" phase, and μ is the coefficient of friction between the rollers and the sack. To prevent the sack from sliding out of the end-effector, the upward friction forces (described in equation 1) must be larger than the total of the maximum weight and the inertial force due to the maximum upward acceleration of the end-effector as shown by inequality (2):

$$2\ \mu\ N_H \geq W_{max}\ (1+\frac{\alpha}{g}) \qquad (2)$$

where g is the gravitational acceleration, W_{max} is the weight of the heaviest sack to be lifted, and a is the maximum upward acceleration of the end-effector induced by the robot or by the material handling device. One must design the end-effector with a large N_H and large μ to guarantee that the heaviest sack that must be lifted by the end-effector cannot slide out. Inspection of Figure 8 shows that the required torque to keep a roller stationary during the "Hold" phase is

$$T_H = \mu\ N_H\ R \qquad (3)$$

where R is the radius of a roller and T_H is the holding torque that should be imposed on each roller during the "Hold" phase. Comparing inequality (2) with equation (3) results in inequality (4) for the required holding torque on each roller during the "Hold" phase.

$$T_H \geq (1+\frac{\alpha}{g})\ R\frac{W_{max}}{2} \qquad (4)$$

If the heaviest sack to be lifted by a particular end-effector is 70 pounds, and the maximum maneuvering acceleration is 0.3g, then if the rollers radius is 0.7", according to inequality (4), one must impose at least 31.85 lbf-inch torque on each roller during the "Hold" phase. Two electric brakes are used on the end-effector to perform the "Hold" process. One must guarantee that the brakes generate sufficient holding torque on the rollers during the “Hold” phase. If the ratio of the angular speed of input shaft to the angular speed of output shaft of speed reducer transmission is N, then the required braking torque for the brake can be calculated from inequality (5).

$$T_B = \frac{T_H}{N} \geq (1+\frac{\alpha}{g})\ R\ \frac{W_{max}}{2N} \quad (5)$$

where T_B is the minimum required torque for the brake. In our experimental design, a normally engaged electric brake was used. Note that the holding torque of a brake is a function of the stiffness of the spring that is installed in the brake. The stiffer the brake spring, the more holding torque can be generated. Although more holding torque during the "Hold" phase assures that heavier sacks can be lifted, one must consider a trade-off: a brake with a stiff brake spring, and consequently large holding torque, requires a large amount of electrical energy to disengage. Designers must make sure that there is sufficient energy available in the electric power source that supplies the brakes. Usually the required electric current to disengage a brake at a given voltage is given by brake manufacturers. The holding torque for the brake used in our experimental setup when the brake is not energized electrically, is 3 lbf-inch. Since the transmission ratio is 36, the holding torque on each roller will be 108 lbf-inch. This is about 2.8 times larger than the required holding torque calculated by inequality (4). The required electric current to disengage the brake is 0.19 Amp at 24 VDC.

During high-speed operations, it is possible for the end-effector to be moved upwardly by the robot before the "Grab" phase is completed. In other words, before the end-effector is in the “Hold” phase, the end-effector is moved upwardly by a robot or by a material handling device. In situations of this nature, to prevent the sack from falling, the electric motors and speed reducers transmissions should generate enough torque on the rollers to assure that the rollers turn inwardly and draw enough sack material between the rollers so the end-effector goes into the “Hold” phase. This means that the required torque to be imposed on a roller during the “Grab” phase should be equal to or larger than the “Hold” torque from inequality (4):

$$T_G \geq W_{max}\ (1+\frac{\alpha}{g})\ \frac{R}{2} \quad (6)$$

Of course inequality (2) must also be satisfied. Inequality (6) offers a value for the grab torque on each roller. An actuator and a transmission must be selected such that the steady state output torque is larger than the largest torque value generated by inequality (6). Through many experiments, it was observed that rollers with radii 0.7" should turn with the speed of about three revolution/second for optimal operation. Small angular speeds for the rollers yield a slow grabbing process, while high speed rotation for the rollers may not allow the rollers to engage and grab the sack material.

6) REMARKS ON PERFORMANCE

The design issue associated with the friction between the rollers and the sack material is described below. An effective 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 usually wears off soon because it is soft. Inspection of inequality (2) shows that large values for μ and for N_H allow the end-effector to lift heavy sacks. However there is a trade-off and one cannot arbitrarily design a end-effector with a large normal force, N_H, and a large μ. Large values for N_H require high torque actuators. In other words, one should not arbitrarily choose a stiff spring to generate a large N_H; if large N_H and μ are chosen to guarantee inequality (2), then a large actuator should also be chosen to overcome friction forces. Stiff springs create large normal force N_H between the rollers and the sack material. A soft rubber surface on the rollers creates a large coefficient of friction between the rollers and the sack material. Practitioners must arrive at a value for the spring stiffness and rubber coefficient of friction so inequality (2) is satisfied with a reasonable margin. Over designed systems (i.e., very a large coefficient of friction and N_H) will lead to an unnecessary large actuator and power supply. On the other hand, if the springs are not stiff enough to generate a sufficiently large N_H to satisfy inequality (2), the rollers will not be pushed against or oppose each other sufficiently, and the sack will slide down.

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