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A Robotic End-Effector for Grasping Sacks

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Abstract

This article describes an end-effector and a method for manipulating 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, comprises two parallel rollers with gripping sur-faces, where the rollers are pushed towards each other. When the end-effector comes onto 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. When sufficient material is caught between the rollers, the rollers stop rotating, whereby the rollers then hold the graspable portion of the object allowing the object to be maneuvered by the robot. When the rollers turn outwardly, the object will be released. The end-effector described here has been evaluated and proven to be effective in grabbing and holding postal sacks since it can grab and hold filled sacks from any point on the sack and regardless of the sack orientation and position. This article describes the underlying principles of the design and grasp control of the end-effector

1. Background on Maneuvering Sacks

Postal services across the world use sacks to hold letters, magazines and small boxes. These sacks which are handled manually by mail handlers are usually filled with magazine bundles, envelopes and parcels, and weigh up to 70 lbs. In general, several factors contribute to awkward and uncomfortable sack handling process for mail handlers:

- the heavy weight of the sacks;
- the lack of handles, eyelets or any other helpful operator interface on the sacks and parcels;
- unpredictable shape, size, and weight of the sacks.

During repetitive pick and place maneuvers, the above elements have increased the risk of wrist, finger, and back injuries among mail handlers. Figure 1 shows a postal distribution center in San Francisco where thousands of sacks are unloaded off a large slide and either emptied directly onto conveyor belts, or loaded onto carts by hand. The sacks are often very heavy and have no operator interface of any kind, which makes them difficult to grasp. This makes the process very slow and inefficient. Robotic systems with special end-effectors can be installed from above to load the sacks onto either the nearest conveyor belts or onto carts. There are very few limitations; the slide and conveyor belts are clear from above, and the carts used to receive sacks are open on top.

Figure 1: A postal distribution center where thousands of sacks are unloaded off a large slide.

To decrease the risk of injuries and to expedite mail processing, the US Postal Service (USPS) has employed various robotic devices to automate some of its mail handling systems. This paper describes an end-effector that is designed to work with these robotic systems to grab and hold sacks. The followings are the 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 and sizes, 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.

Considering our difficult design requirements on grasp robustness, our extensive literature search on grasp and manipulation did not yield any practical approach that allows us to grasp and hold a sack using an existing multifinger robotic hand. This is because most advanced research efforts described on grasping and planning (e.g 1-5) are appropriate for grasping and manipulating objects with well-defined shapes and geometries that originate from industrial components. Moreover, the robotic end-effectors are designed and built for grasping industrial components. This forced us to design special purpose robotic end-effectors that can grasp only sacks and bags securely; the end-effectors described here cannot grasp boxes or any other objects. References 6 and 7 describe other architectures with details.

2. Basic Principle

Figures 2A, 2B and 2C depict the basic architecture of the grasping mechanism of the end-effector that is used to grab sacks and bags. As shown in Figure 2A, the grasping mechanism comprises four gears. Gear 1, secured to an input shaft, is powered by an actuator (actuator is not shown in Figures 2A, 2B and 2C). The actuator is able to turn gear 1 both clockwise and counter-clockwise. Gear 1 is in contact with two gear 2 and gear 3. A bracket holds the axes of the three gears 1, 2 and 3 such that the gears are free to rotate, but their axes cannot move 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 Figure 2A, while holding gear 4, turns independently of the rotation of gear 3. In other words, the link shown in the Figures 2A, 2B and 2C 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 Figure 2A, gears 2 and 4 always turn in opposite directions. Two rollers are rigidly connected to gear 2 and gear 4 therefore they turn in opposite directions relative to each other. Figures 2B and 2C show two configurations where the link has turned counter-clockwise and brought gear 4 closer to gear 2. The rotation of the link along the dashed line allows the rollers to come in contact with each other or separate from each other. Figure 2C shows a configuration where the link has turned counter-clockwise, causing the rollers to be pushed against each other. In order to push the two rollers against each other without an active force-generating element, a spring (not shown) is installed between the link and the bracket to rotate the link counter-clockwise bringing the rollers close to each other. One method of securing spring is described in later sections; however there are many ways to install a spring to push the link counter-clockwise.

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 3, 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. 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 gears 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.

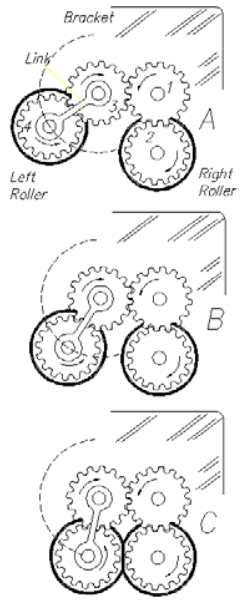

Figure 2: The link shown above is not connected to gear 3 and turns independently of gear 3.

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 gears 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 right roller turns counter-clockwise and the left roller turns clockwise), the sack material, which had been grabbed by the rollers will pass out of the end-effector and the sack will be released. An alternative method of releasing the sack material is to separate the rollers from each other. For good contact between the rollers and sack material, both rollers are preferably covered by material with a large coefficient of friction such as rubber (e.g., Neoprene). If rollers have equal diameters, their angular velocities must be equal so no sliding motion can occur between the rollers. To ensure equal angular velocities for rollers, gears 2 and 4 must be chosen such that n2=n4 where n2 and n4 represent the number of teeth on gears 2 and 4. If the rollers are unequal, gears 2 and 4 must be chosen such that $R_{Right}\, n_2= R_{Left}\, n_4$ where R_{Right} and R_{Left} are the radii of rollers. In general, the rollers must have equal linear velocities at their outer surfaces so no sliding motion can occur between the rollers.

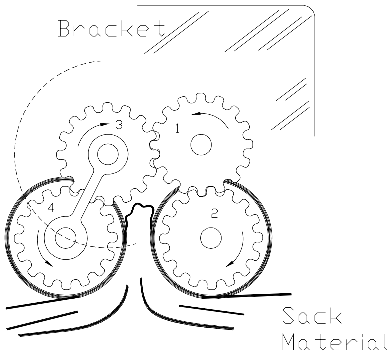

Figure 3: When the rollers are turned inwardly, the sack material will be grabbed and dragged into the end-effector.

3. Prototype System

Figures 4 and 5 show two different views of an end-effector designed for USPS applications where the grasping mechanism shown in Figures 2A, 2B, 2C and 3 is adopted. A mounting bracket supports the major components of the end-effector. Although it could be of any shape, for the sake of saving weight and volume, an L-shape was used for the construction of the mounting bracket. A supporting bracket assembly is installed on the horizontal section of the L-shape mounting bracket and supports the entire grasping mechanism described in Figures 2A, 2B, 2C and 3. As shown in Figure 5, the actuator that turns the rollers comprises an electric motor coupled to a speed reducer transmission. A single-phase 0.2HP DC motor, which is 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, and the output torque at 180 RPM is 70 lbf-in. 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, preventing the motor shaft from turning. When the brake is electrically powered, it is not engaged and the motor shaft is free to turn. In our prototype system, the brake produces 7 lbf-inch of braking torque. A driver sprocket is secured to transmission output shaft of the speed reducer transmission. The rotation of driver sprocket drives a driven sprocket via a chain. The driven sprocket turns a shaft that turns underneath the horizontal plate. The entire grasping mechanism depicted schematically in Figures 2A, 2B, 2C and 3 (including four gears 1, 2, 3 and 4) is installed underneath of horizontal plate and is powered by the driven sprocket.

Figure 6A shows underneath of the end-effector where the rollers have been removed. Two clamping brackets have been installed tightly on a clamping shaft, and rotate together around the axis of the swivel shaft along the shown arrow. This mechanism plays the same role as the link plays in Figure 3; that is, it moves the center of gear 4 along the shown arrow. Gear 1 and gear 3 turn in opposite directions relative to each other. Gears 2 and 4 are in contact with gears 1 and 3, and turn in opposite directions relative to each other. Due to the motion of gear 4 (along the shown arrow), gear 4 moves relative to gear 2, but never makes contact with gear 2. In other words, gears 2 and 4 are never engaged with each other, but rotate in opposite directions to each other. Figure 6B shows the system where two rollers are added and rigidly connected to gear 2 and gear 4, and therefore turn in opposite direction relative to each other. The motion of the axis of gear 4 along the shown arrow, allows the axis of the front roller to move relative to the axis of rear roller while they are both spinning, in opposite directions, along their own axes. Figure 6B also illustrates a spring that pushes the front roller against the rear roller. A wire rope passes through the spring and is secured to a lower bracket. A clamp is secured to the upper end of wire rope by a clamp. The clamp secures the wire rope to the upper end of spring. The spring can be preloaded by moving the clamp along the wire rope. As the clamp is lowered, more compression force is created in the spring. The generated tensile force in wire rope rotates the lower bracket. This causes the front roller to be pushed against the rear roller. Figure 7 shows one possible configuration for installation of a switch to issue a signal when enough sack has been collected in between the rollers. 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. 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 the swivel shaft has turned in a clockwise direction due to the force from sack material, and the switch is pressed against another stationary bracket.

4. Control

In our prototype sysytem, the end-effector comprises a system of detectors or switches installed on the end-effector to control its operation. The end-effector has three primary operational phases: (i) "Grab," *i.e.*, rotating the rollers inwardly, (ii) "Hold," *i.e.*, preventing the rollers from rotating in any direction, and (iii) "Release," *i.e.*, rotating the rollers outwardly. Depending on the application and sequence of operation, the end-effector can be forced into any of the three phases. The logic of how the end-effector is forced into a particular phase depends on how and where the end-effector is being used.

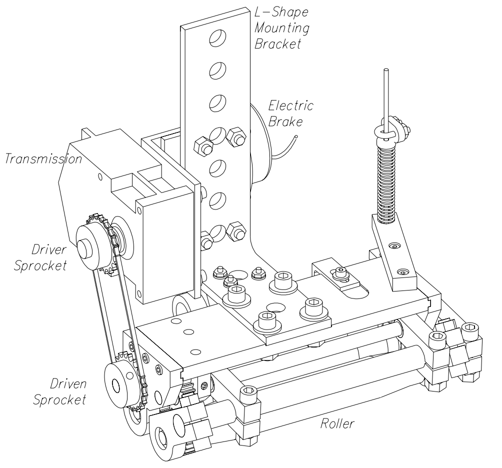

Figure 4: A driver sprocket is secured to transmission output shaft of the speed reducer transmission.

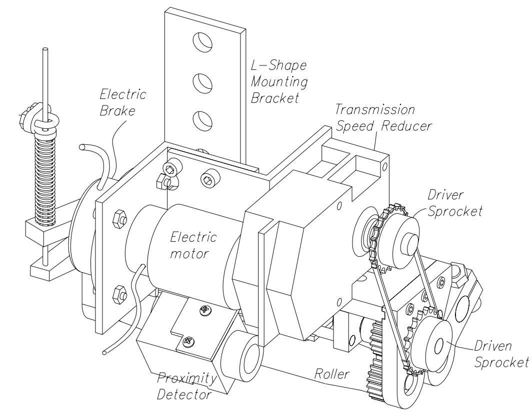

Figure 5: The actuator includes an electric motor and a transmission speed reducer.

A logic signal, S_G, is used to indicate the proximity of the end-effector to a sack to be grasped. In the prototype end-effector, a proximity detector is installed on the end-effector which generates a signal (S_G becomes 1) when the end-effector is in close proximity to a sack. Figure 5 shows the end-effector where a proximity detector is located on the end-effector on a mounting plate. The mounting plate is configured to have an appropriate angle.

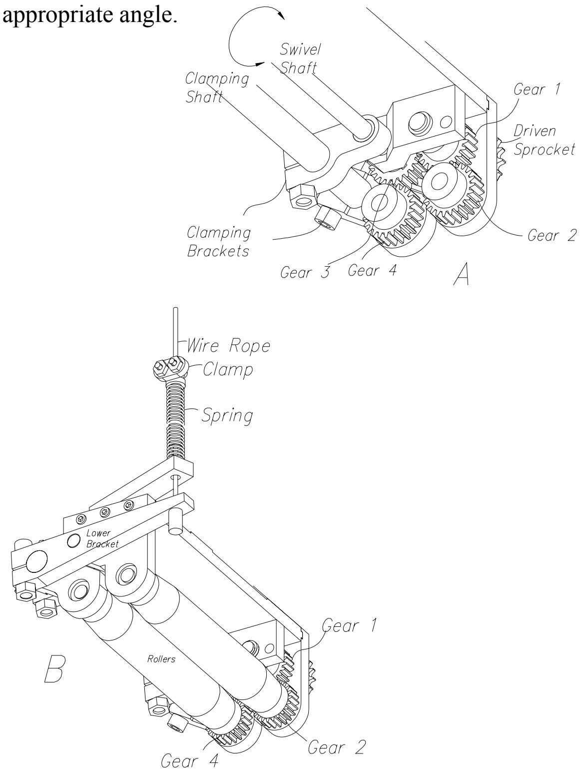

Figure 6: A: Beneath the end-effector when the rollers are removed; B: a spring that pushes the rollers.

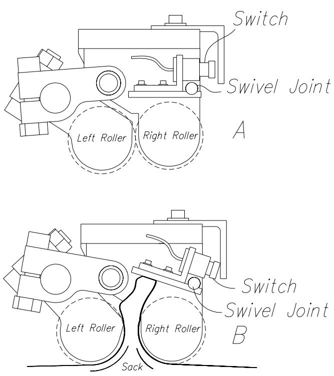

Figure 7: A switch issues a signal when enough sack material has been collected in between the rollers.

Another logic signal, S_H, is issued when sufficient sack material has been dragged in between the rollers. In our experimental system, an electro-mechanical switch, installed in the end-effector, sends a signal (S_H becomes 1) when sufficient sack material has been dragged in between the rollers. This switch was described above in Figures 7A and 7B. Finally, a third logic signal, SR, is issued to release the sack. This signal may be generated by various events. In one example, the sack is released when the sack is placed on the floor, table or other desired surface. In another example, the sack is released upon a command from a computer or from an operator. Figure 8 illustrates the operational phases of the end-effector for all possible combinations of the states of the three signals: S_G, S_H and SR. As shown in Figure 8, there is only one combination of signals S_G, S_H and SR which forces the end-effector into the "Grab" phase. This combination is shown in row 5 where S_G is "1" (the end-effector is close to the sack); S_H is "0" (the sack is not completely grabbed) and SR is "0" (no command is issued to release the sack). As also shown in Figure 8, there are three combinations (rows 1, 3 and 7) that force the end-effector into the "Hold" phase. Row 1 indicates the operation of the end-effector when; no sack is in the end-effector, 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 is gathered between the rollers, therefore, the end-effector holds the sack regardless of the state of S_G. The remaining combinations (rows 2, 4, 6, and 8) indicate the end-effector is forced into the "Release" phase. The end-effector is forced into the "Release" phase when SR is "1" regardless of the states of S_G and S_H.

	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**

Figure 8: The operational phases of the end-effector.

Using the three logic signals, S_G, S_H and S_R, the control system permits the device to operate in each operational phase. In the "Grab" phase of the end-effector, the rollers are rotating inwardly to draw sack material into the end-effector. In the "Release" phase the rollers are rotating outwardly to eject material from the end-efector. In the prototype system, when voltage is applied to the brake coil, the brake will disengage allowing the rollers to rotate. When the end-effector is in the "Hold" phase, the power will be disconnected from the brake.

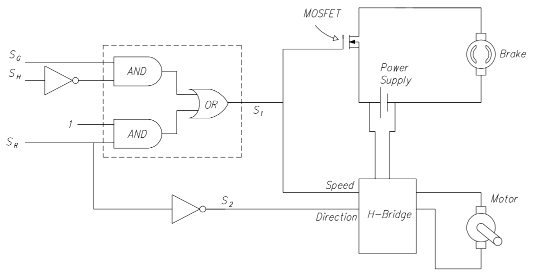

Figure 9: Three signal sources, S_G, S_H and S_R, are wired for accomplishing the operational phases of the End-effector.

Figure 9 schematically illustrates an electronic circuit showing how the three signal sources, S_G, S_H and S_R are wired for accomplishing the events and operational phases shown in Figure 8. A logic chip set that contains OR and AND gates is used to generate an appropriate logic signal based on the states of the three signals: S_G, S_H and S_R. Both S_G and S_R are connected to input pins of two AND gates and of logic chip. The S_H signal is first inverted by an inverter gate and then passed to AND gate. Figure 9 shows two additional signals generated by inverter and OR gate. Signal S1 is tied to two power electronic components: a MOSFET and an H-Bridge. MOSFET acts like a switch; so that, as long as signal S1 is low, *i.e.* $S_1 = 0$, no current flows from power supply to brake. When signal S_1 is high, *i.e.* $S_1 = 1$, MOSFET permits electric current flow from power supply to brake. As discussed above the brake is normally engaged and therefore, the brake permits rotation of the driver sprocket only when it is electrically powered. Among its other pins, H-bridge has two major input pins: "Speed" and "Direction." Both "Speed" and "Direction" pins are connected directly to S_1 and S_2. H-Bridge has two output power terminals that connect directly to the motor.

5. Grasp Conditions and Design Questions

1) Prior to Grasp

Usually prior to any grab and lift process, the sack is rested on a floor or other surface such as a conveyor belt. Figure 10 shows the end-effector right roller in its initial engagement with the sack material. The normal vertical force between the roller and the sack material is N_G. N_G is the function of the normal vertical force being imposed on the end-effector and the weight of the end-effector. The more the robot pushes on the end-effector, the greater the normal vertical force, N_G, will be. The friction forces onto the sack from each roller, μN_G, should be larger than the tension force, T_S, of the sack material.

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

The rollers of the end-effector might not be able to properly engage with the sack material if the end-effector is not pushed downwardly with sufficient force and if the coefficient of friction between the sack and the roller is small. To initiate the grasp successfully, therefore, both μ and N_G should be sufficiently large to satisfy inequality (1). The torque needed to be imposed on the roller during this phase is:

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

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

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

By inspection of Figure 3, the total grasp torque needed to be imposed on gear 1 by the electric motor is:

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

where R_{Right} and R_{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. If inequality (4) is satisfied during this phase, then the grabbing process will start successfully and sufficient sack material will be drawn between the rollers. Over-stuffed sacks can result in a large tensile force and therefore it can be difficult to start the "Grasp" process.

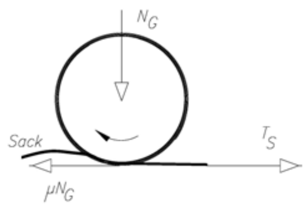

Figure 10: A roller in its initial engagement.

2) During Grasp

As shown in Figure 11, after enough sack material is collected between the rollers, the pressure built up in between the rollers pushes them apart from one another as the sack material is squeezed between them. Suppose the pressure between the sack material and the roller per unit length of the roller's perimeter (circumference) is P, then equation (5) represents the force balance for the right roller along the horizontal direction.

$$R \int_0^{\pi/2} \left(p \ \mathrm{Sin} \ (\theta) + p \ \mu \ \mathrm{Cos} \ (\theta) \right) d\theta = N_H \tag{5}$$

where N_H is the horizontal force on the roller due to the force of the spring. It is rather difficult to know the exact shape of the pressure profile on the rollers, but since the sack material is compliant, it will move between the rollers so an almost uniform pressure is created on the rollers. Substituting a constant value for P into equation (5) results in equation (6) for force N_H :

$$RP_o \int_0^{\pi/2} \left(\mathrm{Sin} \ (\theta) + \mu \ \mathrm{Cos} \ (\theta) \right) d\theta = N_H \tag{6}$$

Or: $$P_o R \, (1 + \mu \ ) \geq N_H \tag{7}$$

where P_o is the constant pressure on the rollers. The torque that turns the rollers should be sufficiently large to overcome the friction forces due to the pressure on the rollers. Figure 11 shows that the torque on the roller during this phase, T_{Roller}, should be larger than the torque imposed on the roller by the friction forces:

$$T_{Roller} \geq \int_0^{\pi/2} P R^2 \mu \, d\theta \tag{8}$$

Substituting the constant value of P_o for P in inequality (8) results in inequality (9) for the torque on the right roller during this phase.

$$T_{Roler} \geq P_o R^2 \mu \, \pi \frac{1}{2} \tag{9}$$

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

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

Inequality (10) shows that the grasp torque on a roller is proportional to the normal force generated by the spring. Inequality (10) also shows that the larger the force between the rollers due to the spring, the larger torque is needed from the motor and the transmission. By inspection of Figure 3, equation 11 shows the total torque that should be imposed on gear 1 by the electric motor and the transmission during this phase.

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

If the electric motor and the transmission cannot provide the torque represented by inequality (11), the rollers will be stalled.

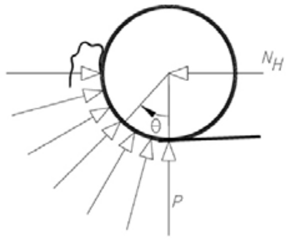

Figure 11: Pressure Profile on the End-Effector Roller.

3) After Grasp

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 motor and speed reducer 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. When the sack is held between the rollers and the end-effector is lifted (Figure 12), 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 due to the maximum upward acceleration of the end-effector as shown by inequality (12):

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

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, μ is the coefficient of friction between the rollers and sack, and α is the maximum upward acceleration of the end-effector induced by the robot or by other material handling devices. If inequality (12) is not satisfied, the sack will slide out of the end-effector. Inspection of Figure 3 also shows that the required grab torque imposed by the electric motor to keep gear 1 stationary is:

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

where R_{Right} and R_{LEft} are the radii of the rollers and T_G is the grab torque that is imposed by the motor and the transmission on gear 1. n_x is the number of teeth on gear x. Comparing inequality (12) with equation (13) results in inequality (14) for the required grab torque on gear 1 for this phase.

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

If the rollers have equal radii, (*i.e.*, $R_{Right} = R_{Left}$), 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. $n_2 = n_4$). The holding torque when the rollers have equal radii can be calculated from equation (15):

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

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 values for the grab torque 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 TS gets larger, inequality (4) approaches inequality (14). In other words, inequality (14) yields a larger value for grab torque than inequality (4). Also note that inequality (11) usually results in a smaller value for the grab torque than inequality (14). It is preferred to choose an electric motor and transmission such that their torque capability is more than what inequality (14) prescribes. The motor and the transmission must be able to provide more torque, for a short time, to accommodate for the transient inertia torque due to acceleration of rotating elements of the end-effector.

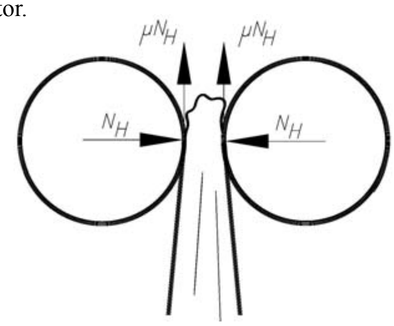

Figure 12: The friction forces between the rollers and the sack prevent the sack from sliding out.

4) 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 due to 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 inequality (14):

$$T_{Brake} \geq W_{max}\ (1+\frac{\alpha}{g}) \left[R_{Right}\frac{n_1}{n_2} + R_{Left}\frac{n_1}{n_4} \right] \frac{1}{2} \qquad (16)$$

If the brake torque is not large enough to satisfy inequality (16), the sack will slide out of the end-effector. If the rollers have equal radii, (i.e., $R_{Right} = R_{Left}$), 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. $n_2 = n_4$). The holding torque when the rollers have equal radii can be calculated from equation (17):

$$T_{Brake} \geq W_{max}\ (1+\frac{\alpha}{g})\ R_{Right}\ \frac{n_1}{n_2} \qquad (17)$$

In our first design, both gears 1 and 2 have equal number of teeth and both rollers have equal radii. If the heaviest sack to be lifted by a particular end-effector is 70 pounds (a sack or object containing weight is referred to as a "weighted" sack or object), and the maximum maneuvering acceleration is 0.3g, then if the rollers radii is 0.7" and $n_1 = n_2$, according to inequality (4), one must impose at least 63.7 lbf-inch of braking torque on gear 1 during the "Hold" phase. Therefore, if the ratio of the angular speed of the transmission input shaft to the angular speed of gear 1 is N, the minimum required brake torque, TB, is N times smaller than T_H. In our experimental design, we have chosen N=36, $n_1 = n_2$ and rollers have equal radii.

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 spring of the brake, the more holding torque can be 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. In our experimental system, a normally engaged brake was used which uses 0.477 Amp at 12 VDC to disengage. The holding torque for the brake, when the brake is not energized electrically, is 7 lbf-inch. Since the transmission ratio is 36, the holding torque on gear 21 will be 252 lbf-inch. Also note that the speed reducer transmissions will not be back-drivable if they have large speed reduction ratios. This helps the end-effector during the "Hold" phase since the rollers will not spin outwardly by the force of the sack weight and therefore the sack material will not be released. In general the use of speed reducers that are non-back drivable may eliminate the need for brakes in the end-effector device.

6. Conclusion

We developed an end-effector that can grab any point of a sack without any operator intervention and regardless of how the sack is laid on the floor, on a table, or on a conveyor belt. An entirely different and effective concept for grasping sacks was developed and was described here. 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. The end-effector described here

- grabs a sack from any point on the sack.
- does not require the edge of the sack to be gathered and flattened prior to grasp.
- does not require t he 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.)
- does not require operator intervention for grasp.
- does not use the weight of the sack to lock and secure the sack in the end-effector.

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