Mechanism For Grasping Deformable and Undefined Shape Object

Bhatt Kumar K[1*], Vijay Chaudhary[2]

[1]Mechanical Engineering/CAD-CAM/ME, Charotar Institute of Technology, Changa, India
[2]Mechanical Engineering/CAD-CAM/ME, Charotar Institute of Technology, Changa,India

[*] Corresponding author (email: erbhatt@gmail.com)

Abstract

When the objects are deformable and of undefined shapes and size like sacks (*borrie's*), it would be difficult to grasp it with the help of robot. This paper describes the grasping mechanism for the deformable objects like the bags, sacks etc which have an undefined shapes, size and dimensions. The end-effectors mechanism has been developed which will fullfill the above requirement. Here the principle of friction is used to lift the sacks between the two rollers. The sacks are get suck between the rollers randomly due to the friction between the surface of sacks and roller material. The sacks are held firmly and transported to the required place easily, where the roller move outward so the sacks are withdrawn out of the end effectors rollers. 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 remark.

Keywords: Robot, End effector, Mechanism

1. Introduction

In the handling of large numbers of deformed objects the automation plays very important role, but still it is slow against the quantity to handle. For example in the post departments lots of sacks came every day and they have to be sorted and place them in different container as per the destination. The considerable weight of these sacks, their lack of handling, eyelets, or other operator interfaces, and the unpredictable shape and size of the packages which create awkward and uncomfortable handling predicaments for mail handlers.Previousouly robots with dexterous type fingers were used to pick and place [1], which require the object to be recognized in shape or any parameter and also the location. 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. These sacks, handled manually by mail handlers, are often filled to 70kg in weight with magazine bundles, envelopes, and parcels.

For mail handlers, the key contributing factors to awkward and uncomfortable manual handling processes are:

a) The considerable weight of the sacks;
b) The lack of handles, eyelets or other helpful operator interfaces on the sacks and parcels;
c) Inconsistency in shape, size, and weight of the sacks in a workstation.

During repetitive pick and place maneuvering, the above factors have shown to lead to increased risk of wrist, finger, and back injuries among mail handlers. Mainly two types of activities are noticed in the postal sacks handling. One is transfer of sacks from the slide to a cart or a conveyor belt and other is sorting of the sacks. The postal sacks are having a weight ranging from 10kgf to 32kgf .Each sack sorter has the carts arranged around the roller. The study at the station had given the parameter for the design of end-effector different mechanism to handle it. The end-effector must be able to grab and hold a sack of any shape and size from any point on the sack. The robot and the end-effector must grasp and manipulate these sacks continuously for long periods without dropping any of them. 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 have to enter the robot cell for recovery, which results in process downtime for cell shutdown and robot re-initialization for grasp operation. Therefore, the robot bandwidth will be the limiting factor in overall system throughput.

Fig. 1: Distribution Centre of Sacks

1.1 Background History

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. The two-point grasping is insufficient and unstable. 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*. [2] describe a four-finger pneumatically powered hand. Jau [3] presents a four-finger electrically powered hand capable of creating rolling motion for objects. Salisbury [4] gives details on an electrically powered three finger hand with stiffness control. Recent progress by Hirai and Wada [5], 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. Sugano and Kato [6] describe the design of a five-finger hand for playing musical instruments with little grasping and manipulation capability.

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. 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.

2. Principle of Grasping

The end-effector mechanism comprise of the four numbers of gears as shown in Fig. (2a). Gear 1, in contact with Gear 2 and Gear 3, is secured to an input shaft and powered by an actuator, 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. (2a), while holding Gear4,turns independently of the rotation of Gear 3. In other words, the link shown in the Fig. (2a) to Fig. (2d) is able to position the axis of Gear 4 at any point on the dashed line regardless of the rotation of the gears. The surfaces of the rollers may be knurled, grooved, stippled, or covered by frictional material such as soft rubber.

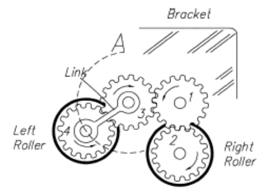

Fig. 2a

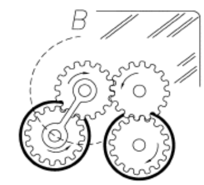

Fig. 2b

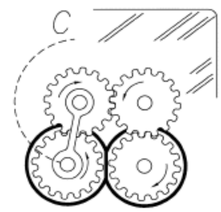

Fig. 2c

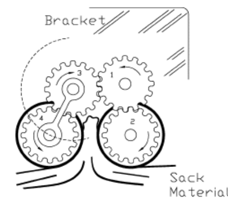

Fig. 2d

Fig. 2: End Effector Mechanism

When the rollers turn inward and come in contact with the sack as seen in Fig. (2d), 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 n2 = n4 where n2, n4 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 $R_{right} * n4 = R_{left} * n2$, where R_{right} and R_{left} are the radii of right and left rollers respectively shown in Fig. (2a).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 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.

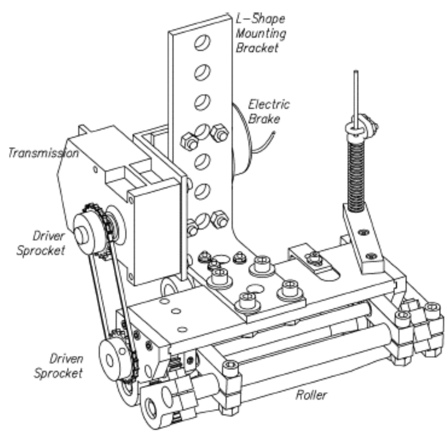

Fig. 3: End Effector Assembly

A supporting bracket assembly is installed on the horizontal section of the L-shape mounting bracket to support the entire grasping mechanism as shown in Fig. (3).The actuator required for turning the rollers is comprised of an electric motor of 0.2HP DC coupled to a speed reducer transmission with power supply from 12V DC. Additionally, the speed reducer transmission has a speed ratio of 36, resulting in output torque 31.5kgf-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. 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 as shown in Fig. (4). Two clamping brackets are installed tightly on a clamping shaft, rotating together around the axis of the swivel shaft along the arrow shown. Gears 1 and 3 turn in opposite directions 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. (5) 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.

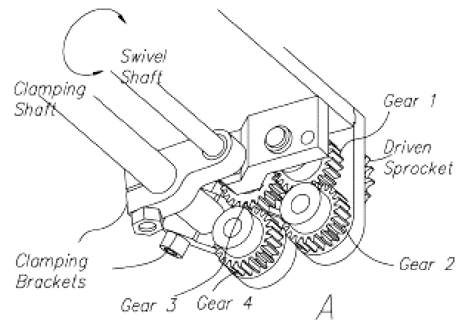

Fig. 4: Underneath the Mechanism

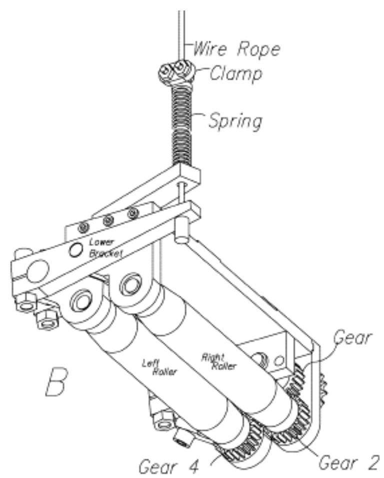

Fig. 5: Roller attachment

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. (6) 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. (6) shows the end-effector with the swivel shaft in its neutral position, with the switch deactivated. Fig. (7) 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 9kgf.

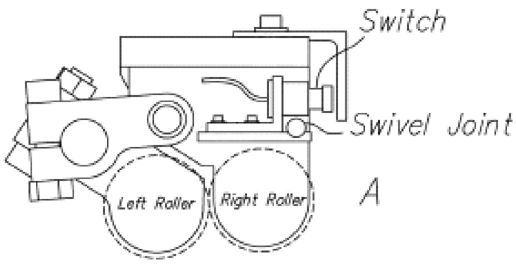

Fig. 6: Switch location for signal

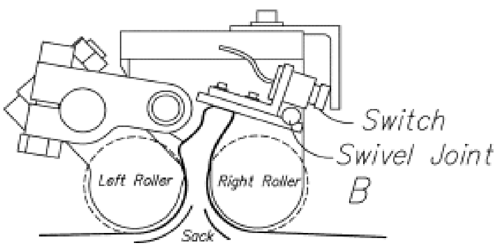

Fig. 7: Switch Location for Signal

3. Control of Mechanism

There are total of four steps in the total procedure of grasping:
1) Grab, i.e., rotate the rollers inward.
2) Hold, i.e., lock the rollers.
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. 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.3) asserts $S_G = 1$ when the end-effector comes in close proximity to a sack. The logic S_H signal 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 when sufficient sack material is collected between the rollers. 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. Table (1) 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 below table, 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).

Table 1: Control Logic Table

	S_G	S_H	S_R	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

There are three combinations to force the end-effector into the "Hold" phase. Row 1 indicates a case in which the sack is neither in nor near the end-effector, and no release is command 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. The above table (1) illustrates schematically how the three signals $S_{G,}$ S_H and S_R, drive the events and operational phases.

3.1 Grasp and Hold Conditions

3.1.1 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. (9) 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 the end-effector. The sacks are usually filled with heavy objects which results in a tensile force, present in the sack material. If this tensile force $\boldsymbol{t_S}$ 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 **(μN_G)** should be larger than the tension force $\boldsymbol{t_S}$ of the material, so the sack material can be pulled into the area between the rollers

$$\mu N_G \geq t_s \qquad \textbf{(1)}$$

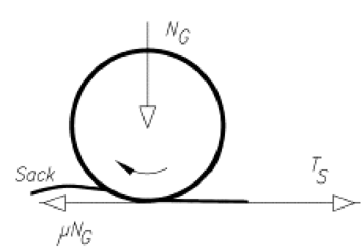

Fig. 8: Force acting on the roller

The tensile force in the sack $\boldsymbol{t_S}$ 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 μ and N_G should be sufficiently large to satisfy Eq. (1). The torque needed to be imposed on the roller during this phase can be calculated as,

$$T_{Roller} = \mu N_G R \quad (2)$$

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

$$T_{Roller} \geq t_s R \quad (3)$$

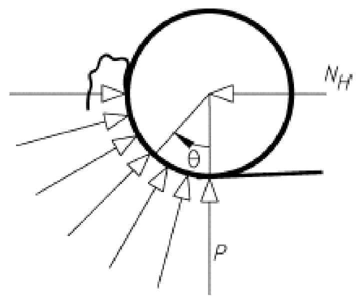

Fig. 9: Pressure profile on end-effector roller

By inspection of Fig. (3), the total grasp torque needed to be imposed on Gear 1 by the electric motor is

$$T_G \geq t_S \left[\left\{R_{Right}\left(\frac{n1}{n2}\right)\right\} + \left\{R_{Left}\left(\frac{n1}{n4}\right)\right\}\right] \quad (4)$$

Where R_{Right} and R_{Leftt} 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 Eq. (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.

3.1.2 During Grasp

As shown in Fig. (10), 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, Eq. (5) represents the force balance for the right roller along the horizontal direction.

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

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 P value for into Eq. (5) results in Eq.(6) for force N_H .

$$RP_o \int_0^{\frac{\pi}{2}} (\sin(\theta) + \mu\cos(\theta))\, d\theta = N_H \quad (6)$$

$$RP_o(1+\mu) = N_H \quad (7)$$

Where P_0 is the constant pressure on the rollers. The torque turning the rollers, should be sufficiently large to overcome the frictional forces from the pressure on the rollers.

$$T_{Roller} \geq \int_0^{\frac{\pi}{2}} PR^2 \mu\, d\theta \quad (8)$$

Substituting the constant P_0 for P in Eq. (8) results in Eq. (9) for the torque on the roller during this phase.

$$T_{Roller} \geq P_o R^2 \mu\, \pi \frac{1}{2} \quad (9)$$

Substituting for P_0 from Eq. (7) into Eq. (9) results in a relationship between the force, and the required torque on the roller T_{Roller} as,

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

Eq. (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. (2d), Eq. (11) shows the total torque that should be imposed on Gear 1 by the electric motor and the transmission during this phase as,

$$T_G \geq \frac{\mu\pi}{2(1+\mu)} N_H \left[\left\{R_{Right}\left(\frac{n1}{n2}\right)\right\} + \left\{R_{Left}\left(\frac{n1}{n4}\right)\right\}\right] \quad (11)$$

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

3.1.3 After Grasp

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.

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

(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 magnitude of the maximum total acceleration of the end-effector induced by the robot. If Eq. (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 μ sufficiently large to ensure that the heaviest sack will not slide out of the rollers. Inspection of Fig. (2d) shows that the required grab torque imposed by the electric motor to keep Gear 1 stationary is T_G,

$$T_G = \mu N_H \left[\left\{R_{Right}\left(\frac{n1}{n2}\right)\right\} + \left\{R_{Left}\left(\frac{n1}{n4}\right)\right\}\right] \qquad (13)$$

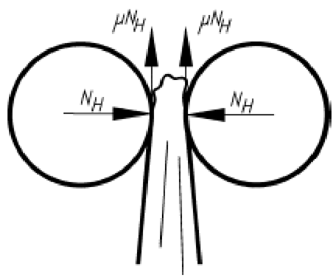

Fig. 10: Friction forces prevent the sacks from sliding

Where R_{Right} and R_{Leftt} 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 Eq. (12) with Eq. (13) results in Eq. (14), which represents the required grab torque on Gear 1 for this phase.

$$T_G \geq W_{max}\left(1 + \frac{\alpha}{g}\right)\left[\left[\left\{R_{Right}\left(\frac{n1}{n2}\right)\right\} + \left\{R_{Left}\left(\frac{n1}{n4}\right)\right\}\right]\right]\frac{1}{2} \qquad (14)$$

If the rollers have equal radii, (i.e. $R_{Right} = R_{Leftt}$), 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.*n2* = *n4*,). The holding torque, when the rollers have equal radii, can be calculated from Eq. (15) below,

$$T_G \geq W_{max}\left(1 + \frac{\alpha}{g}\right) R_{Right}\frac{n1}{n2} \qquad (15)$$

In our first design, both Gears 1 and 2 have equal number of teeth and both rollers have equal radii. Three inequalities Eq. (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 Eq. (4), (11) and (14). The largest value for t_S, the tension force in the sack material, occurs when the sack is lifted. As $\boldsymbol{t_S}$ gets larger, Eq. (4) approaches Eq. (14). In other words, Eq. (14) yields a larger grab torque value than Eq. (4). Since Eq. (11) typically results in a smaller grab torque value than Eq. (14), it is preferable to choose an electric motor and a transmission with a torque capability greater than what Eq. (14) prescribes.

3.1.4 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 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 Eq. (14).

$$T_H \geq W_{max}\left(1 + \frac{\alpha}{g}\right)\left[\left[\left\{R_{Right}\left(\frac{n1}{n2}\right)\right\} + \left\{R_{Left}\left(\frac{n1}{n4}\right)\right\}\right]\right]\frac{1}{2} \qquad (16)$$

If the brake torque is not large enough to satisfy Eq. (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. $R_{Right} = R_{Leftt}$), 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. *n2* = *n4*). When the rollers have equal radii, the brake torque T_B can be calculated from below equation,

$$T_B = \frac{1}{N} W_{max}\left(1 + \frac{\alpha}{g}\right) R_{Right}\frac{n1}{n2} \qquad (17)$$

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.

4. Conclusion

From the above concept we can make an small, handy and light weight end effector which can be used for value addition to the pick and place activity in automation ,especially for deformable and undefined shape objects like postal *borries*. So this type of mechanism can be used to automize and speed up the work in the large postal offices where the lots of sacks have to handle and the workman energy can be utilized somewhere else.

Acknowledgement

I am very much thankful to Prof. H. Kazerooni for there help in study of this topic and Dr. Y. P. Kosta, Dean-Faculty of Technology and Engineering, Charotar University of Science and Technology, Changa for their guidance, encouragement and support in undertaking this work.

References

[1] G. Casalino, G. Cannata, G. Panin, and A. Caffaz, "On a two-levels hierarchical structure for the dynamic control of multifingered manipulation," in *Proc. IEEE Int. Conf. Robotics Automation*, vol 1, Seoul, Korea, pp. 77-84, May 2001.

[2] S. C. Jacobsen, I. K. Iversen, D. Knutti, R. T. Johnson, and K. B. Biggers, "Design of the Utah/MIT dextrous hand," in *Proc. IEEE Int. Conf. Robotics Automation*, Sanfrancisco CA, pp. 1520–1532, Apr-May 1986.

[3] B. M. Jau, "Man-equivalent telepresence through, four fingered humanlike hand system," in *Proc. IEEE Conf. Robotics Automation*, vol. 1, Nice, France, , pp. 843–848, May 1992.

[4] J. K. Salisbury, "Design and control of an articulated hand," in *Proceedings Inernatinal on Design and Synthesis,* okyo, Japan, 1984.

[5] S. Hirai and T. Wada, "Indirect simultaneous positioning of deformable objects with multipinching fingers based on uncertain model," *Robotica*, vol. 18, pp. 3–11, 2000.

[6] S. Sugano and I. Kato, "Wabot-2: autonomous robot with dexterous finger-arm coordination in keyboard performance," in *Proc. IEEE Conf. Robotics Automation*, vol. 4, Raleigh, NC, pp. 90-97,March 1987.