A Robotic End-Effector for Grabbing and Holding Compliant Objects

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1. SUMMARY

The device discussed here is an end-effector that can be used with robotic and material handling devices to maneuver compliant objects with undefined geometry and shapes such as sacks and bags. The end-effector is connected from its base to the end point of a robot or a material handling system and provides an interface between the material handling device and a sack. Using the invention described here, a sack can be lifted from any point and with any orientation. When the end-effector makes contact with a sack, it will grab and hold the sack tightly, maintaining its hold even during a power failure. The sack will be released either by an operator input or automatically based on an occurrence of an event. This application describes the hardware architecture, the control method and the design issues associated with the end-effector.

Figure 1 depicts a practical method of constructing an end-effector to grab bags. Consider the four gears of Figure 1 Gear 1 is powered by a motor (motor is not shown) and is able to turn in both clockwise and counter-clockwise. Gear 1 is in contact with two gears 2 and 3 where both gears turn along the same direction. A bracket holds the axes of three gears 1, 2 and 3 such that the three 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 counter-clockwise. The axis of gear 4 is held by a structure and while it is in contact with gear 3. By inspection of Figure 1, it can be observed that gears 2 and 4 always turn in opposite directions. Figure 2 shows the end-effector where rollers are rigidly connected to gears and therefore turn in opposite direction relative to each other. If two rollers are rigidly connected to two gears 2 and 4, the rollers will turn along their own axes, but in opposite directions relative to each other. In order to push two rollers against each other without any active force, generating element, a spring must be used. For the sake of clarity in the figures, no spring is shown, however there are many ways to install a spring to push rollers against each other. As the rollers turn inward, the sack material gets dragged in between the rollers. For good contact between the rollers and sack material, both rollers can be covered by material such as rubber with a large coefficient of friction. 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 the rollers, gears 2 and 4 must be chosen such that $n_2=n_4$ where n_2 and n_4 represent the number of teeth on gear 2 and gear 4. If rollers have unequal diameters, gears 1 and 4 must be chosen such that $R_2 \times n_2 = n_4 \times R_1$ where R_2 and R_1 are the radii of rollers. In general, it is desirable to ensure that rollers have equal linear velocities at their outer surfaces so no sliding motion occurs between the rollers.

2. TORQUE CALCULATION

One important design issue is the calculation of the required torque to keep the rollers stationary (i.e. when the sack material is dragged in between the rollers and the rollers have stopped turning). When the sack is held between the rollers and the end-effector is lifted, the total upward friction forces imposed on the bag by rollers is calculated by equation (1):

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

Where N_H is the normal force imposed by the rollers onto the sack material during the "Hold" phase and μ is the coefficient of friction between the rollers and 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 inertia force due to the maximum upward acceleration of the end-effector as shown by inequality (2):

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

where g is the gravitational acceleration, W_{max} is the weight of the heaviest sack to be lifted, and α is the maximum upward acceleration of the end-effector induced by the robot or by the material-handling device. If inequality (2) is not satisfied, the sack will slide out of the end-effector. Therefore 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 an end-effector does not slide out of the rollers. Inspection of Figure 1 shows that the required torque on gear 1 to keep gear 1 stationary during the "Hold" phase is

$$T_H = \mu N_H \quad R_1 \frac{n_1}{n_2} + R_2 \frac{n_1}{n_4}. \tag{3}$$

where R_2 and R_2 are the radii of rollers and T_H is the holding torque that should be imposed on gear 1 during the "Hold" phase. n_x is the number of teeth on gear x. Comparing inequality (2) with equation (3) results in inequality (4) for the minimum holding torque on gear 21 during the "Hold" phase.

$$T_H \geq W_{max} (1+\frac{\alpha}{g}) \left[R_1 \frac{n_1}{n_2} + R_2 \frac{n_1}{n_4} \right] \frac{1}{2} \tag{4}$$

If rollers have equal radii, (i.e. $R_2 = R_1$), 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 rollers have equal radii can be calculated from equation (5):

$$T_H \geq W_{max} (1+\frac{\alpha}{g}) R_2 \frac{n_1}{n_2} \tag{5}$$

In the first application, 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, and the maximum maneuvering acceleration is 0.3g, then if the rollers radii is 0.7" and $n_{21} = n_{22}$, according to inequality (5), one must impose at least 63.7 lbf-inch torque on gear 1 during the "Hold" phase.

If a brake is used to create holding torque, one must guarantee that the brake and the transmission have enough holding torque on gear 1 during the "Hold" phase. If the ratio of the angular speed of the transmission input shaft (motor output shaft) to the angular speed of gear 1 is N, then the minimum required brake torque, T_B, can be calculated from inequality (6).

$$T_B = \frac{1}{N} T_H \geq W_{max} (1+\frac{\alpha}{g}) \quad R_2 \frac{n_1}{n_2} + R_2 \frac{n_1}{n_4} \Bigg] \frac{1}{2N} \tag{6}$$

We recommend that practitioners choose a brake with more torque capacity than this to compensate for inefficiencies and uncertainties in various components of the end-effector. In our first prototype 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, one must consider a trade-off; a brake with a stiff spring and consequently large holding torque requires a large amount of electric current to disengage. Designers must make sure that there is enough electric current available in the electric power supply that feeds the brake. In the first form of this invention, a normally engaged brake manufactured by Inertia Dynamics was used. This brake uses 0.477 Amp at 12 VDC to disengage. Normally engaged brake means that the brake does not allow any rotation for the motor shaft when the brake is not electrically powered. 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 1 will be 252 lbf-inch.

As discussed earlier, rather than using a brake, one can use other mechanisms (e.g. ratchet) to lock gear 1 during the "Hold" phase. In the design of any locking systems such as locking ratchets, one must guarantee that the required torque on gear 1 during the "Hold" phase can be generated by the locking system.

To prevent the sack from falling, electric motor 42 and its transmission 43 (Figure 3) should generate enough torque on gear 21 to guarantee that the rollers turn and bring enough sack material between the rollers should the sack slides down. This means that the required torque to impose on gear 1 should be equal to the torque from inequality (4):

$$T_G \geq W_{max}\,(1+\frac{\alpha}{g} \quad R_{27}\frac{n_{21}}{n_{22}} + R_{28}\frac{n_{21}}{n_{24}}\Big]\frac{1}{2} \qquad (7)$$

Of course if rollers have equal radii, inequality (17) leads to inequality (18):

$$T_G \geq W_{max}\,(1+\frac{\alpha}{g})\,R_{27}\frac{n_{21}}{n_{22}} \qquad (8)$$

We used an actuator and a transmission system that has 70 lbf-in steady state output torque was used. We recommend that practitioners choose a DC motor with more torque capacity to compensate for inefficiencies and uncertainties in various components of the end-effector. Of course the actuator 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.

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 slow grabbing process while high-speed rotation for the rollers may not allow the rollers to engage and grab the sacks. If the angular speed of the gear 21 is ω revolution/seconds, the required power during the "Grab" phase is:

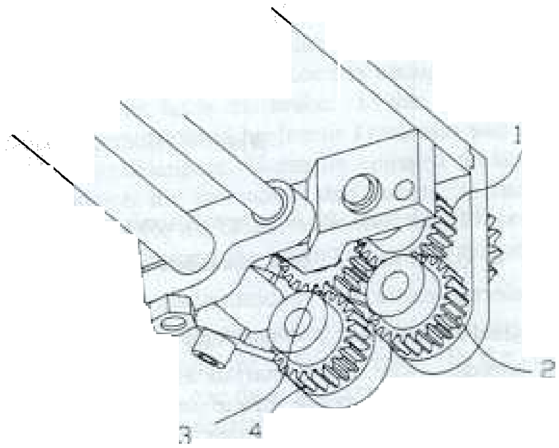
$$\text{Power} = \frac{T_G\ \omega}{1050} \qquad \text{HP} \qquad (9)$$

$$\text{Power} = \frac{T_G\ \omega}{1.4} \qquad \text{Watt} \qquad (10)$$

Where the unit of T_G is lbf-inch and ω is in revolution/second. Substituting for T_G (i.e. 70 lbf-inch) and ω (i.e. 3 rev/sec) into equations (19) and (20) results in 0.2 HP or 150 Watt for the electric motor at 3 revolution/second (180 RPM). Note that the end-effector was designed such that $n_{21} = n_{22}$ and therefore gear 21 and rollers turn at the same angular speeds. The above analysis also yields a size for the required current if electric motor is used to impose torque on gear 21. If a DC power supply, with the voltage V, is used to power motor 42, then the required current by the motor is calculated by inequality (11).

$$I_M \geq \frac{T_G\ \omega}{1.4\,V} \qquad \text{Amp} \qquad (11)$$

If a 12VDC power supply is used to power the actuator, then minimum current drawn by the motor is 12.5 Amp. If both actuator and brake are powered with the same power supply, the required current for the brake needs to be supplied in addition to the required current for the motor.



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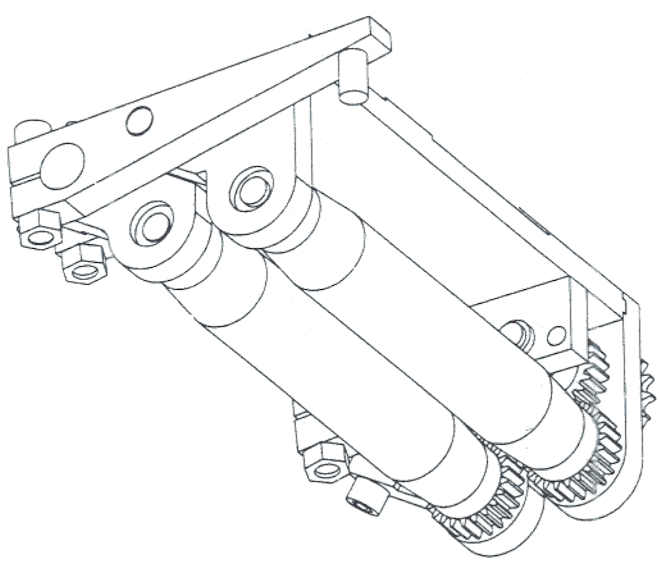

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